Naval Research Laboratory
Washington, DC 20375-5320

NRL/MR/7120--00-8424

Coherent Acoustic Communications During the Littoral Warfare Advanced Development 99-1 Experiment

Azmi Al-Kurd
Jeffrey Schindall

Acoustic Signal Processing Branch
Acoustics Division

May 22, 2000

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave Blank*)

2. REPORT DATE

May 22, 2000

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE

Coherent Acoustic Communications During the Littoral Warfare Advanced Development 99-1 Experiment

5. FUNDING NUMBERS

6. AUTHOR(S)

Azmi Al-Kurd and Jeffrey Schindall

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory
Washington, DC 20375-5320

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/MR/7120--00-8424

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
Code 32
Arlington, VA 22217-5660

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

Coherent acoustic communication experiments were performed during the Littoral Warfare Advanced Development exercise in the Gulf of Mexico in February 1999 (LWAD 99-1). The Acoustic Communication (ACOMM) experiment was allotted four segments of 5 hours each and two segments of one hour each. The ACOMM waveforms were projected using two mid-frequency acoustic sources (F-80 and F-56) and received at multiple platforms using vertical line arrays (VLA), sonobuoys (SSQ-57A), a submerged acoustic receiver, and TAN/SQS-53C sonar system. The ACOMM modems were aboard the Sea Diver platform; both modems were in the receiving mode. The received signals were processed *in situ* and stored on DAT tapes and 8-mm TEAC tapes for post experimental analysis. The analysis of the LWAD 99-1 experiment data shows strong multipath acoustic propagation environment, the first arrival weaker than later arrivals, and low signal-to-noise ratio (SNR). The reception at the deep VLA's (Sea Diver and Edwin Link) was very weak (almost absent) throughout the experiment. Data analysis using single phone reception without diversity resulted in high bit error rate (BER). The BER was drastically reduced when 4-channel spatial diversity was implemented, provided that there was sufficient SNR (> 10 dB) and the Doppler shift estimate was accurate.

14. SUBJECT TERMS

LWAD 99-1 experiment	Communications	ACOMM
ACOMMS	Coherent communication	
Digital acoustic	Underwater communication	

15. NUMBER OF PAGES

41

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102

Coherent Acoustic Communications During the Littoral Warfare Advanced Development 99-1 Experiment

A. Al-Kurd and J. Schindall

Naval Research Laboratory

Washington, DC 20375

Abstract

Coherent acoustic communication experiments were performed during the Littoral Warfare Advanced Development exercise in the Gulf of Mexico in February 1999 (LWAD99-1). The Acoustic Communication (ACOMM) experiment was allotted four segments of 5 hours each and two segments of one hour each. The ACOMM waveforms were projected using two mid-frequency acoustic sources (F-80 and F-56) and received at multiple platforms using vertical line arrays (VLA), sonobuoys (SSQ-57A), a submerged acoustic receiver, and TAN/SQS-53C sonar system. The ACOMM modems were aboard the Sea Diver platform, both modems were in the receiving mode. The received signals were processed *in situ* and stored on DAT tapes and 8 mm TEAC tapes for post experimental analysis. The analysis of the LWAD 99-1 experiment data show strong multipath acoustic propagation environment, the first arrival weaker than later arrivals, and low signal-to-noise ratio (SNR). The reception at the deep VLA's (Sea Diver and Edwin Link) was very weak (almost absent) throughout the experiment. Data analysis using single phone reception without diversity resulted in high bit error rate (BER). The BER was drastically reduced when 4-channel spatial diversity was implemented, provided that there was sufficient SNR (> 10 dB) and the Doppler shift estimate was accurate.

I. Introduction

The Littoral Warfare Advanced Development (LWAD) program, sponsored by the Office of Naval Research, provides cost-effective, at-sea, proof-of-concept experiments for littoral undersea warfare science and technology projects that have high potential for near-term transition to Fleet systems.

The complexity of underwater communications stems from the complexity of the oceanic environment. The ocean represents a band-limited and rapidly fading communication channel in which the multipath structure is temporally unstable due to random fluctuations. Coherent data

Manuscript approved March 13, 2000.

transmission using quadrature phase shift keying (QPSK) allows for efficient use of the available bandwidth.

The ACOMM experiment was divided into two parts; the main part which constituted 4 segments of 5 hours each, these segments were called events 01, 02, 03, and 04. The secondary part which comprised event 05 was divided into two segments of one hour each and they were called event 05, and 05a. The participating assets during the main part of the ACOMM experiment were the R/V Gyre, the R/V Edwin Link, and the R/V Sea Diver. Two Navy assets participated in the second part of the experiment, one asset with a 53C in a receiving mode, and the other asset with a submerged receiver. The R/V Sea Diver did not participate in the second part of the experiment. During both parts of the experiment the R/V Gyre was a designated source ship. The R/V Edwin Link and the R/V Sea Diver were the designated receiver ships.

The main part of the ACOMM experiment started on JD 037 at 21:55:00 zulu and ended on JD 038 at 21:03:00 zulu. The first segment of the secondary part (event 05) started on JD 040 at 02:10:00 zulu and ended on JD 040 at 03:00:00 zulu. The second segment of the secondary part of the ACOMM experiment (event 05a) started on JD 041 at 00:02:00 zulu and ended on JD 041 at 01:00:00 zulu.

The ACOMM waveforms were projected by a mid- frequency acoustic source towed by the R/V Gyre. The ACOMM waveforms were QPSK modulated with data rates of 1000, 1500, and 2000 b/s. The signals projected by the towed source were received and recorded at the other two platforms using VLAs. The VLAs on board the R/V Sea Diver platform were dedicated receiver-processors (real-time *in situ* processing). The VLA on board the R/V Edwin Link was an alternate receiver with 32 elements. The received signals were recorded on DAT tapes aboard the Sea Diver and they were recorded on 8 mm TEAC tapes aboard the Edwin Link.

During the experiment the modem triggered and started processing the received data at the selected baud rate whenever there was sufficient signal-to-noise ratio (SNR). The results of the real-time processing were saved to files on Iomega zip disks. The starting point of a detected data packet and an indicator of the mean square error (MSE) were displayed. This information gave indication about the quality of the received signals and the performance of the receiver, but it was not sufficient for the operator to make substantial changes to the modem parameters at-sea.

Post-experimental analysis showed a very strong multipath acoustic propagation environment, and very often the first arrival was weaker than the later arrivals. Also, it showed that the SNR was very low during most of the experiment which rendered the equalization process to be very difficult. These results point out many issues that remain to be researched

II. EXPERIMENT SITE, ASSETS AND ENVIRONMENTAL DATA

The LWAD 99-1 experiment was conducted in the Gulf of Mexico from February 05, 1999 to February 14, 1999. The ACOMM experiment events 01, 02, 03, and 04 started February 06 at 16:55 local time (JD 037 at 21:55 zulu) and ended February 07 at 16:03 local time (JD 038 at 21:03 zulu). The ACOMM experiment event 05 started February 08 at 21:10 local time (JD 040 at 02:10 zulu) and ended February 08 at 22:00 local time (JD 040 at 03:00 zulu), event 05a started February 09 at 19:02 local time (JD 041 at 00:02 zulu) and ended February 09 at 20:00 local time (JD 041 at 01:00 zulu). The experiment is described in detail in the LWAD 99-1 Experiment Test Plan [1] and the LWAD 99-1 Quick Look Proceedings [2]. The experiment site (in the Gulf of Mexico off the western coast of Florida) is shown in Fig. 1. The ocean bottom at this site is hard and nearly absent of sediment. During most of the LWAD 99-1 experiment the Sea State was 3 to 4, except during the ACOMM segment where the Sea State was estimated at 2. Four general types of surfical and underlying geology lie within the experiment area [3]. The central section consists of a foram sand with sandwaves common. Acoustic work in the area has revealed that the sand is muddy calcareous sand. To the west of the central section lies the Howell Hook Reef which is of Pleistocene age and acts as a sediment trap. Shoreward of the central section lies the Pulley Ridge and the oozed covered inner shelf, both areas are underlain by carbonate sequence.

Three platforms were involved in the ACOMM exercise: the R/V Gyre, the R/V Edwin Link, and the R/V Sea Diver. The R/V Gyre was a dedicated source ship with two towed acoustic sources (F56 and F80), only one source was transmitting at a time and the other source was a spare. The R/V Sea Diver was a dedicated receiver and signal processing ship. The Sea Diver had the following gear on board: two acoustic modems for real-time *in situ* processing, data acquisition and recording systems, and two 16 element dual aperture VLAs (eight phones were spaced for high frequency, 20 kHz, and eight phones were spaced for mid-frequency, 3.5 kHz,). Each VLA was connected to an acoustic modem, only 8 elements (the mid-frequency part) on each VLA was activated and the output signals from each VLA were recorded on DAT tapes using 8-channel Sony recorder. The R/V Edwin Link was a dedicated receiving platform with a 32 element VLA (LWAD VLA). A 32 channel TEAC recorder was used to record the received acoustic data at the Edwin Link. The first 28 channels recorded the acoustic signals from the upper 28 phones on the LWAD VLA and the last 4 channels recorded the received signals at the sonobuoys tethered to the Edwin Link and the Sea Diver. The Sea Diver was a moored platform and the Edwin Link was a drifting platform (Sea Diver lat. 25.37.15 N long. 84.11.02 W, and Edwin Link lat. 25.37.4 N long. 84.08.6 W). The R/V Gyre was a moving platform.

The water column in the operation area (OPAREA) was about 160 meter deep and the mixed layer extended down to about 20 meters. Figure 2 shows a family of 10 sound speed profiles (SSP) measured during the ACOMM exercise at the Edwin Link site. The first SSP was measured on February 6, 1999 at 18:54 local time, and the last SSP was measured on February 7, 1999 at 17:02 local

time, see the right margin in Fig. 2. The acoustic source was at an approximate depth of 22 m when the R/V Gyre was underway at 4 Knots, and it was at an approximate depth of 45 m when the R/V Gyre was dead-in-the-water (DIW). The ACOMM VLA-A and VLA-B were at approximate depths of 45 m and 18 m, respectively. Both arrays were deployed from the moored R/V Sea Diver. During Event 02 Leg CD at 09:15 zulu VLA-A and VLA-B were raised 3 meter to new approximate depths of 42 m and 15 m, respectively. The LWAD VLA was deployed to an approximate depth of 50 m over the stern of the drifting R/V Edwin Link. At the beginning of Event 04 (at 18:00 zulu) the LWAD VLA on the R/V Edwin Link was raised to an approximate depth of 15 m (in the layer). During the ACOMM experiment, sonobuoys were deployed in pairs (one shallow and one deep) from the Sea Diver, the Edwin Link, and from the Gyre whenever it became DIW. The RF sonobuoys' data were recorded at the R/V Edwin Link and the R/V Gyre.

III. Projected Waveforms

Prerecorded QPSK and offset QPSK (OQPSK) modulated pseudo-random (PRN) sequences were transmitted by mid frequency towed sources (F80 and F56). The acoustic source F-80 (aboard the R/V Gyre) was replaced by the acoustic source F-56 during the second half of Event 02 (JD 037 at 08:22 zulu).

Four prerecorded DAT tapes with four different ACOMM signals were generated for transmission during LWAD 99-1 events 01 to 04. Each tape had one hour of ACOMM signals which followed a pre-specified structure. Figure 3 shows the signal pattern used for ACOMM transmission. Each transmitted signal group (pattern) covered 40 seconds which included 1 sec CW signal followed by 4 sec of silence, then 1 sec PRN QPSK or OQPSK coded signal followed by 4 sec of silence, then 5 sec of PRN QPSK or OQPSK coded signal followed by 5 sec of silence, and finally 10 sec of PRN QPSK or OQPSK coded signal followed by 10 sec of silence. The transmitted signal pattern was repeated 90 times to cover one hour of transmission. Each PRN signal contained a 13 symbol Barker code followed by 300 ms of silence and then the PRN data sequence, Fig. 4.

The four tapes differed in the CW frequency preceding the PRN sequences and by the data rate of the PRN sequences. Table 1 lists the parameters of the various signals which were prerecorded on the DAT tapes for transmission. The carrier frequency for the PRN sequences was at 3550 Hz. Figure 5 shows a sample transmitted signal (and its spectrum) from each tape.

Table 2 shows the transmitted signals during the four ACOMM events, also, it indicates the duration of each Leg, the time shown is in zulu and each event comprised of 6 Legs. It is worth mentioning that Table 2 follows the planned execution of the ACOMM experiment as shown in Fig. 6, except for the duration of the various Legs and the sequence of the transmitted waveforms during Event 04. The arrows in Fig. 6 represent the R/V Gyre movement and the rectangles on the arrows represent the location where the Gyre was planned to be DIW. The point A in Fig. 6 represent the midpoint between the Sea Diver and the Edwin Link, and the numbers on the arrows represent the start and end time of that Leg referenced to the beginning of the given event. Each event was

planned for 5 hours transmission. Figure 7 shows the actual tracks of the R/V Gyre during the ACOMM four events.

According to Table 2, Tape A was transmitted during Event 01 along the Legs AB, CD, DD, and DA; during Event 02 along Leg AC; during Event 03 along Leg BB, CA, and AD; during Event 04 along Leg DA. Tape B was transmitted during Event 01 along Leg BA; during Event 02 along Legs AB, CD, DD, and DA; during Event 03 along Leg DA. Tape C was transmitted during Event 01 along Leg AC; during Event 02 along Leg BA; during Event 03 along Legs AB and BC; during Event 04 along Legs AB and BB. Tape D was transmitted during Event 04 along Legs BC, CA, and AD. In event 04, Leg BC was negligible (less than 5 min) and Legs CA and AD were combined into one Leg (CD).

IV. ACOMM VLA Pre-Experiment Test

Both ACOMM VLA-A and VLA-B were tested before the experiment to determine the response of the different phones on both arrays. A "tap" test was performed for all phones on board the Sea Diver. Then, both arrays were deployed in the water (while the ships were in port) to verify reception of acoustic signals that were transmitted by the Edwin Link sonar. Table 3 shows the connection of VLA-A and VLA-B phones to the modem channels and the status of each phone.

A. Mid-Frequency Section

The following test was performed for the upper 8 phones (phones number 9 through 16) on both arrays (VLA-A and VLA-B), see Fig. 8.

A.1. Test Setup:

1. Both arrays (VLA-A and VLA-B) were deployed from the aft of the Sea Diver while in port at Harbor Branch at 14:15 local time on February, 03, 1999. They were deployed to an approximate depth of 4 m from the sea surface. Water depth was about 7 m.

2. The Edwin Link transmitted frequent chirp pulses between 2kHz and 8kHz.

3. VLA-A was connected to Modem A and VLA-B was connected to Modem B.

4. Modem A output was fed to the Precision Filter channels 0 through 7.

5. Modem B output was fed to the Precision Filter channels 8 through 15.

6. The Precision Filter is a low pass-filter with cut of frequency of 5 kHz.

7. The gain on the Precision Filter was set to 10 dB for all channels.

8. Modem A through the precision filter was connected to Sony recorder PC –108M.

9. Modem B through the Precision Filter was connected to Sony recorder PC-208 Ax.

A.2. Test Results

1. The chirp was received clearly on both arrays and monitored using the spectrum analyzer, oscilloscope, and the loud speaker.

2. All channels showed strong SNR between 2 to 5 kHz, except channel 7 on Sony recorder A, which corresponds to phone number 15 on VLA-A, see Fig. 8.

B. HIGH FREQUENCY SECTION

The following test was performed for the lower 8 phones (phones number 1 through 8) on both arrays (VLA-A and VLA-B), see Fig. 8.

B.1. Test Setup

Same setup as in part A with the exception that the cables from the lower section of the array (phone 1 to 8) were connected to the precision filter and to the corresponding modems A and B, see Table 3.

B.2. Test Results

1- The chirp was received clearly on both arrays and monitored using the spectrum analyzer, oscilloscope, and the loud speaker.

2- All channels showed strong SNR between 2 to 5 kHz, except channels 1 and 8 on Sony recorder A which corresponds to phone numbers 1 and 8 on VLA-A, and channel 7 on Sony recorder B which corresponds to phone number 7 on VLA-B, see Table 3.

C. TEST CONCLUSION:

Phones number 1, 8, and 15 on VLA-A are very noisy and might be dead. Phone number 7 on VLA-B is dead. The rest of the phones on both arrays showed good SNR.

V. RECEIVED SIGNALS

The main part of the ACOMM experiment started on JD 037 at 21:55 zulu and ended on JD 038 at 21:03 zulu. The first segment of the second part (event 05) started on JD 040 at 02:10 zulu and ended on JD 040 at 03:00 zulu. The second segment of the second part of the ACOMM experiment (event 05a) started on JD 041 at 00:02 zulu and ended on JD 041 at 01:00 zulu.

During the main segments of the ACOMM experiment (events 01 to 04) signals were received on the R/V Sea Diver, the R/V Edwin Link, and on sonobuoys. The received signals on the Sea Diver

were recorded on 4 mm DAT tapes using two 8 channel Sony recorders. Recorder A was attached to phones 9 to 16 on the ACOMM VLA-A (deep VLA), and recorder B was attached to phones 9 to 16 on the ACOMM VLA-B (shallow VLA). The received signals on the Edwin Link by the LWAD VLA were recorded on TEAC 8 mm tapes using a 32 channel TEAC recorder. The first 28 channel on the TEAC recorder were used to record the upper 28 phones of the LWAD VLA, Fig. 9, and the last 4 channels on the TEAC (channels 29, 30, 31, and 32) were used to record the data from the sonobuoys tethered to the Sea Diver and to the Edwin Link. Table 4 shows the deployment schedule of the sonobuoys tethered to the Sea Diver and the Edwin Link.

In general, the received signal on the Sea Diver showed poor SNR (less than 10 dB) most of the time during Event 01 and Event 02. The reason for this low SNR was attributed to the low power output from the acoustic source (F-80). An attempt to increase the source level at the R/V Gyre failed and the acoustic source F-80 was replaced by the source F-56 during Event 02 Leg AC at 08:22 zulu. The F-56 acoustic source seemed to output more energy than F-80. At least this was the case at the beginning of the F-56 deployment, at that time the received CW signals on VLA-B showed greater than 10 dB SNR according to the readings from the spectrum analyzer. Then at about 09:10 zulu the SNR dropped to less than 5 dB (according to the readings from the spectrum analyzer) and stayed low through the remainder of Event 02 and the first half of Event 03. It was reported by the Gyre at 11:49 zulu that the source level was 149 dB. Source malfunction was reported at 12:01 zulu. The source was retrieved for repair and redeployed at 13:00 zulu. The transmission recommenced at 13:29 zulu and it was reported by the Gyre that the source level was 166 dB. The SNR of the received signal at the Sea Diver noticeably increased according to the spectrum analyzer readings (SNR of the CW signal increased to the range of 10 to 15 dB for a large portion of the time until the end of the experiment at 21:03 zulu).

VI. Post Experimental Analysis

A. Received Signal Characterization

The transmission loss (TL) was calculated using the environment data from the experiment site. This calculation was performed using the University of Miami Parabolic Equation [4] (UMPE) code where the ocean was assumed to be range independent. The sound speed profile (SSP) used for this calculation is a measured SSP by the Edwin Link during the ACOMM experiment, Fig 10 (A). Figure 10 (B) shows the TL as a function of range and depth when the source is at 20 m bellow the surface, and Fig. 10 (C) shows the TL when the source depth is at 40 m. It is worth noting that the dynamic effects of the medium, such as the surface roughness, volume scattering, internal waves and other random medium generating factors, are not included in this calculation. We notice that the acoustic energy, for both source depths, is channeled within the layer. During the experiment, the received signal was very weak on both receiving platforms (Sea Diver and Edwin Link) when a VLA was deployed deep (greater than 40 m). The SNR of the received signal was drastically improved whenever a VLA was deployed within the layer (less than 20 m).

Due to the problems associated with the acoustic source during the events 01, 02, and the first half of event 03, we concentrated our efforts for post experimental analysis on the received data during the second half of event 03 (Legs CA, AD, and DA) and during event 04 (Legs AB, BB, BC, CA, AD, and DA), since event 04 was cut short (Leg BC was eliminated). Leg BC in event 04 is included here to maintain the order and consistency of the events. Also, Leg CA in event 04 was extended to be Leg CD where the OQPSK signals were transmitted, again, in order to maintain consistency we divide it into two parts Leg CA and Leg AD.

A sample received signal during event 04 along Leg DA on VLA-B at the Sea Diver is shown in Fig. 11, where QPSK signals with data rate of 1000 b/s and CW signals at 3100 Hz were transmitted. Figure 11 (A) shows the time series of the received signal (B) shows the spectrogram of the signal and (C) shows the power spectral density (PSD) of the received signal. The different sections of the signal group (pattern: 1 sec CW followed by 4 sec silence, 1 sec PRN followed by 4 sec silence, 5 sec PRN followed by 5 sec silence, and finally 10 sec PRN signal followed by 10 sec of silence) and the spectrum of the CW and PRN signals are clearly identifiable.

Figure 12 shows the variation of the received signal on different phones of VLA-B during event 04 Leg DA when the Gyre was towing the acoustic source inbound. It is obvious that the received signal level on a given phone varies with time, this variation is due mainly to the range change between the receiver and source. Also, it shows that the oceanic channel response is not uniform across the signal bandwidth which leads to drastic received signal fluctuation on a given phone.

Channel 2 on modem B which corresponds to phone 10 on VLA-B showed no signal during all Legs of event 03 and event 04. This phone malfunction was not predicted during the VLA pre-experiment test; see Table 3. Also, phones 13 and 14 (channels 5 and 6) on VLA-B showed very suspect signals (noisy) which might be a result of the phones malfunction.

It is of interest to investigate the signal fluctuation while the source is DIW (there is virtually no range variation between the source and receiver). Figure 13 shows the spectrogram of the received signals on the VLA-B at the Sea Diver when the source was DIW during event 04 (Leg BB). At that time a CW signal at 3300 Hz and QPSK signal with data rate of 2000 b/s were transmitted. Channels 2, 5, 6, and 7 which correspond to phones 10, 13, 14, and 15, are very noisy. Investigating the received signals on the other phones, we notice the strong signal fading with time on any given phone. Also, we notice the received signal fluctuation and variation at a given time on different phones. Therefore, these plots demonstrate the temporal and spatial fluctuation of the received signals.

Figure 14 shows the spectrogram of the received signals on channels 1 and 8 during event 03. Plots A and B represent the signals received during Leg CA while plots C and D represent the signals received along Leg DA. These plots show the spectrogram of the combined received PRN and CW signals. Both Legs (CA and DA) represent inbound motion of the source ship. The signal

fading and fluctuation in time and frequency are evident. Also, the variation between the received signals on two phones separated by 1.5 m (the distance between phone 9 and 16) is evident from these plots.

B. SIGNAL TO NOISE RATIO

As mentioned before, our efforts will concentrate on the analysis of the received signals during the second half of event 03 (Legs CA, AD, and DA) and event 04 (Legs AB, BB, CD, and DA). In this report we estimate the SNR from the 5 sec PRN sequence; therefore, the time separation between two successive SNR estimates is 40 sec. The noise level is found by calculating the variance of the signal over 100 ms during the silence period preceding the reception of the 5 sec packet. The signal level is estimated by taking the variance of the signal over 100 ms around the middle of the 5 sec packet.

Figure 15 plots the SNR as a function of time for the received PRN signals on channels 1, 3, 4, and 8 (VLA-B phones 9, 11, 12, and 16). Figure 15 (a, b, c) shows the SNR during event 03 along Legs CA, AD, and DA, respectively. Figure 15 (d, e, f) shows the SNR on the same phones during event 04 along Legs AB, BB, and DA, respectively.

Figures 15 shows the range effect on the SNR where the SNR trend is up-slope when the source is moving inbound (Event 03 Leg CA and Leg DA; Event 04 Leg DA) and it is down-slope when the source is moving outbound (Event 03 Leg AD; Event 04 Leg AB). We notice that the SNR for the received PRN signals varies significantly for different runs (Legs). Also, the SNR along a given Leg fluctuates drastically from one received packet to the other. The reason for this fluctuation is not known. Is it due to the environment and the signal propagation? Or is it due to the source malfunction? Further investigation needs to be conducted to answer these questions.

C. CHANNEL IMPULSE RESPONSE

The temporal variability of the oceanic channel is estimated by deducing the channel response function from the received PRN signals. The channel response is estimated by convolving the received Barker code with the conjugate of the time reversed transmitted Barker code. In this report we include the estimate of the channel response from the Barker codes preceding the 5 sec PRN sequence. Therefore, the time separation between two successive channel estimates is 40 sec.

Figure 16 shows a color image of the channel response to the transmitted Barker codes during the above mentioned events (03 and 04), the horizontal axis shows the correlation delay time in ms and the vertical axis shows the transmission time in seconds. The multipath arrivals of the broadband signals are evident in these plots. We have aligned the main arrivals (strongest arrival) in order to show the difference in the arrival time of the secondary arrivals (weaker arrivals). The best way to measure the channel stability is when the source and receiver are stationary, but the

channel response estimation during that time (event 04 Leg BB) is not accurate in Fig. 16 (e), due to the weakness or absence of the received signals, see Fig. 15 (e).

The channel response and the multipath structures are very unstable and continuously changing, as shown in Fig. 16 a, b, c, d, f, g. It is worth noting that these plots represent the channel response estimation over a short range (source/receiver separation of less than 5 km), channel estimation at larger distance was not possible due to the low SNR at the receiving array. Also, we notice that the first arrival is weaker than the later arrivals in most of the data. This type of environment is very challenging for the equalizer, since the main arrival is not always the first arrival.

Figure 17 shows samples of the channel impulse response estimation during event 04 along Leg AB. These samples correspond to horizontal slices from Fig. 16 (d). These plots show detailed variations of the channel impulse response with the progression of time. In reference to the start of the run (Leg AB), the plots (a, b, c, d, e, f) in Fig. 17 show the channel response at times 400 sec, 440 sec, 640 sec, 680 sec, 1200 sec, and 1240 sec, respectively. It is obvious that the channel impulse response structure changes significantly over a period of 40 sec. The SNR corresponding to these times can be found from Fig. 15 (d).

D. ACOMM Signal Equalization

In this report we present sample equalization results from event 03 along Leg CA, Fig. 18 (a), and from event 04 along Leg AB, Fig. 18 (b), and along Leg BB (source DIW), Fig. 18 (c). These plots represent the bit-error-rate (BER) of the equalized received signal as a function of time. The equalization was performed for the received signals on channel 1 (VLA-B phone number 9), the parameters of the sparse decision feedback equalizer (DFE) were not changed for the different runs, these parameters (used in the Matlab sparse DFE code) are listed in Table 5. Figure 18 shows poor BER for these segments using the received signals on one phone. The implementation of 2-channel spatial diversity (channels 1 and 8) did not improve the BER performance of the receiver, Fig. 19. On the other hand, the implementation of 4-channel spatial diversity (channels 1, 3, 4, and 8) resulted in drastic improvement in the BER performance of the receiver, Fig. 20. The outliers in the convergence regions, Fig 20, correspond to a drop in the SNR, Fig. 15, and/or inaccurate estimation of the Doppler shift during the given transmitted packet, Fig. 21. Figure 21 shows the Doppler shift estimate during Event 03 Leg CA, Leg AD, Leg DA, and during Event 04 Leg AB, Leg BB, Leg DA. The Doppler shift estimate was found using the ambiguity function search method [5].

The inaccurate Doppler shift estimate and/or the poor BER (especially with low number of spatial diversity) can be attributed to two main reasons: first, the SNR was very low most of the time and the SNR fluctuation remains an unanswered question; second, the channel at the experiment site represents a very dynamic environment and very complex multipath structure for mid-frequency propagation, especially at short ranges (less than 5 km).

VII. REAL-TIME *"IN SITU"* PROCESSING

Real-time *"in situ"* signal processing was performed during the LWAD 99-1 on board the R/V Sea Diver. Two acoustic modems based on the SHARC digital-signal-processors (DSP) "ADSP-21062" were used for this purpose. The acoustic modem contained a DSP board with 8 SHARC DSPs, but the software (currently installed) was only able to address one DSP. Therefore, we performed the analysis on a single channel due to the limited computational and memory capabilities of the acoustic modem.

The data processed by the modems were stored in files on 100 MB Zip cartridges. An IOMEGA Zip drive was attached to the parallel port of each acoustic modem. During the experiment we were able only to conclude the modem status from the activities on the computer screen (i.e. received a signal, triggered, waiting for a signal to trigger, or it is processing a received packet). The receiver parameters were not adjusted during the experiment due to the lack of sufficient information about the environment and the condition of the received signals.

The modem would trigger and start processing a received ACOMM packet if the cross correlation between the transmitted and received Barker code exceeded a certain threshold. The cross correlation result might not exceed the threshold due to a weak received signal as a result of excessive transmission loss along the propagation path, or due to severe distortion induced onto the transmitted signal by the propagation environment.

At any given time during the experiment, the receiver modem aboard the R/V Sea Diver was set to receive a particular waveform, i.e., an ACOMM signal with data rate of 1000 b/s, 1500 b/s, or 2000 b/s. The three data rates were transmitted separately along an individual Leg (source path), recall Table 2. Each transmitted signal pattern contained 3 PRN signals, see Fig. 3, but the modem was not able to process the three packets in real time due to its lack of the computation resources. The modem was capable of processing 2/3 of the transmitted packets. One hour of transmission contains 90 signal patterns (groups) which corresponds to 270 PRN packets. It is expected that the modem can process 180 packets per transmission hour.

During event 01, modem A (attached to the deep VLA-A) did not trigger at any received ACOMM data, modem B (attached to the shallow VLA-B) detected 40 PRN ACOMM packets, these detections were concentrated along the end of Leg BA (source/receiver separation less than 3 km). If we consider only the last 15 minutes of Leg BA, then we can say that modem B detected 89% of the transmitted packets, otherwise, it detected only 22% of the packets transmitted during event 01 Leg BA. The packet detection and processing along the other Legs during event 01 were meaningless, because the received signal during event 01 was very weak. Our speculation is that the source was outputting very low energy (less than 150 dB).

During event 02, modem A never triggered (detected) ACOMM data, and modem B detected

ACOMM data for very short period along Leg CD (after the source change took place). Over 10 minutes transmission we could count for 30% detection. The packet detection and processing along the other Legs during event 02 were meaningless.

During event 03, the received signals were very weak along Legs AB. BB, and BC. Along Legs CA, AD, and DA, the ACOMM data detection was about 90% when the source/receiver separation was less than 3 km, it was 40% when the separation was between 3 and 5 km, and it was less than 30% when the separation was greater than 5 km.

During event 04, along Leg AB and after 15 min from the start (less than 3 km from the Sea Diver) the received signal level went down drastically, Fig. 15 (d), and the SNR stayed down until the second half of Leg CD. At about 19:45 zulu we noticed improvement in the SNR and it stayed relatively high for about 30 min, then it went down again. Along Leg DA which started at 20:33 zulu the SNR was low until about 20:45 zulu. In general the ACOMM packet detection was about 90% when the source/receiver separation was less than 3 km, and it was less than 50% when the separation was greater than 3 km.

Data equalization was very difficult during the LWAD 99-1 experiment, this is attributed mainly to the performance of the acoustic source. The best we were able to achieve was a source level of 166 dB which produced a SNR of less than 10 dB at the receiver. The SNR sometimes exceeded 10 dB when the source/receiver separation was less than 3 km. The disadvantage of the short distance propagation in shallow water is the complexity of the channel response; the reverberation and multipath structure are very strong. For more details on short range propagation see references [5, 6].

Quality checking of the received data and receiver parameters adjustment was not possible to perform *in situ* within the allotted time for the ACOMM experiment. On the other hand, if these adjustments were made then the diversity of the collected data would have been very limited. We plan to re-process the recorded data using the modem in the laboratory. This task will be accomplished by playing the raw data from the Sony DAT recorder into the acoustic modem (A/D channels). The obvious advantage of reprocessing the data in the laboratory while adjusting the modem parameters is that there is no need for ship time to repeat the transmission of the acoustic data. Also, with the modified (new version) of the modem software we will be able to process multiple received channels and hence take advantage of the computational capabilities of the 8 SHARC processors installed on each modem.

VIII. Summary and Future Work

Phase coherent acoustic communications data were collected during the LWAD 99-1 experiment. The purposes of the LWAD 99-1 ACOMM experiment were to examine the acoustic communica-

tions performance as a function of range using a moving source, to compare the performance between a moving source and a stationary source, between receivers at different depths and, between receivers at different geographical locations, and finally to examine the at-sea performance of two acoustic modems built by Lockheed - Sanders.

The at-sea data analysis of the Sanders modems were presented in Sec. VII. In general, 90% of data packets (event 03 and event 04) were captured by the modem attached to the shallow VLA when the source /receiver separation was less than at 3 km and 50% or less of data packets were captured at longer ranges. The decrease of the trigger rate is believed to be due to the decreased signal-to-noise ratio as range increased.

Post experimental analysis showed that the signals received at the deep VLA's were very weak and almost absent throughout the experiment. Therefore, the data presented in this report are taken from the shallow VLA aboard the Sea Diver. The SNR was low throughout the experiment, especially during the events 01 and 02 and the first half of event 03. The environment is very dynamic and the channel impulse response structure changes drastically within 40 sec. The BER was very high when we processed the received signals on one or two phones (spatial diversity). The BER improved drastically (over short range) when we used spatial diversity over 4 receiving phones.

There are several technical issues which are still being investigated but not yet resolved. These issues will continue to be addressed in the immediate future. There are also acoustic issues relating to the environmental effect on the modem performance which will be addressed in a separate study.

A. Technical Issues

1. The acoustic source performance was the show stopper for this experiment. It is desired to have SNR of at least 10 dB at the receiver. Therefore, to be able to receive and equalize ACOMM data at mid-ranges (10 to 20 km) it is required to have a source level of at least 190 dB.

2. Acoustic data reception was almost absent on the deep VLA at the Sea Diver. We will investigate the reason for the lack of data from the deep receiver by comparing the data from the deep VLA at the Sea Diver with the data from the deep VLA at the Edwin Link, also we will investigate the data received on the shallow and deep sonobuoys tethered to the Sea Diver and the Edwin Link, also, we will investigate the received data on the sonobuoys deployed by the Gyre while it was DIW (these sonobuoys were in the near field of the source).

3. The ACOMM VLA-A and VLA-B need to be retested and calibrated before going on another experiment.

B. ACOUSTIC ISSUES

1. Almost 23 hours of acoustic transmission data were collected form the LWAD 99-1. Out of that total we may have less than 6 hours of useful data received at different platforms and sonobuoys. This presents a rich data set to study the temporal and spatial (range) variations of the channel impulse response. The channel impulse responses will be analyzed statistically on one hand and analyzed individually on the other hand to see how it affects the sparse equalizer performance.

2. Signal fluctuation statistics will be studied for a single phone versus a single beam pointing to the source (we will use the data received on the 53C and the submerged receiver during event 05 and 05a). It is believed that beam fluctuations are less than the single phone and may aid in signal equalization. Beam signal-to-noise ratio may also improve the communication performance to a longer range than the single phone or multiple phones equalized incoherently.

3. The data will be tested with the performance prediction model [5, 6] which requires a fair understanding of the acoustic channel fluctuations.

ACKNOWLEDGMENT

This work is supported by the Office of Naval Research. We greatly appreciate the participation in the Littoral Warfare Advanced Development program.

REFERENCES

1. LWAD Team, "Littoral Warfare Advanced Development (LWAD) LWAD 99-1 Experiment, Test Plan", Marine Acoustics Inc., Arlington, Virginia. February 1999.

2. Multiple Authors, "Littoral Warfare Advanced Development (LWAD) LWAD 99-1 Quick Look Briefing Proceedings", Marine Acoustics Inc., Arlington, Virginia. 7 April 1999.

3. Bruce R. Gomes, James K. Fulford, and Redwood Nero, "Environmental Characterization for the Littoral Warfare Advanced Development Experiment (LWAD 99-1)", NRL Memorandum Report NRL/MR/7184-99-8218, 27 October 1998.

4. K. Smith, F. Tappert, "UMPE: The University of Miami Parabolic Equation Model", MPL Technical Memorandum 432, May 1993.K. Smith, F. Tappert, "UMPE: The University of Miami Parabolic Equation Model", MPL Technical Memorandum 432, May 1993

5. A. Al-Kurd, and T.C. Yang, "Experimental Evaluation and Statistical Analysis of Coherent Digital Acoustic Communication in Littoral Ocean", U.S. JUA (in press).

6. T.C. Yang, and A. Al-Kurd, "Environmental Impact on Phase Coherent Underwater Acoustic Communications: A Physics Based Approach", U.S. JUA, Vol. 48, No. 3, July 1998.

Table 1:

Tape	CW Frequency (Hz)	PRN Sequences	Data Rate (b/s)
A	3100	QPSK	1000
B	3200	QPSK	1500
C	3300	QPSK	2000
D	3400	OQPSK	1000

Table 2: ACOMM signals transmitted during LWAD 99-1

	Event 01	Event 02	Event 03	Event 04
Leg - AB	TX Tape - **A** 22:03 - 00:10	TX TApe - **B** 05:03 - 06:00	TX TApe - **C** 11:30 - 11:56	TX TApe - **C** 18:00 - 18:30
Leg - BA	TX Tape - **B** 00:15 - 01:09	TX TApe - **C** 06:02 - 08:20		
Leg - BB			TX TApe - **A** 13:29 - 13:53	TX TApe - **C** 18:30 - 19:25
Leg - AC	TX Tape - **C** 01:09 - 02:09	TX Tape - **A** 08:40 - 09:12		
Leg - BC			TX TApe - **C** 13:53 - 14:17	TX TApe - **D** 19:25 - 19:30
Leg - CA			TX TApe - **A** 14:25 - 15:42	TX TApe - **D** 19:30 - 20:00
Leg - AD			TX TApe - **A** 15:42 - 16:23	TX TApe - **D** 20:00 - 20:33
Leg - CD	TX TApe - **A** 02:09 - 02:45	TX TApe - **B** 09:12 - 09:25		
Leg - DD	TX TApe - **A** 02:45 - 03:38	TX TApe - **B** 09:25 - 09:52		
Leg - DA	TX TApe - **A** 03:38 - 03:55	TX TApe - **B** 09:52 - 10:27	TX TApe - **B** 16:33 - 17:04	TX TApe - **A** 20:33 - 21:03

Table 3: Pre-Experiment Test of ACOMM VLA-A and VLA-B

HF Segment Modem Ch.#	MF Segment Modem Ch. #	VLA-A Phone #	Status	VLA-B Phone #	Status
1		1	ok	1	ok
2		2	ok	2	ok
3		3	ok	3	ok
4		4	ok	4	ok
5		5	ok	5	ok
6		6	ok	6	ok
7		7	ok	7	dead phone
8		8	ok	8	ok
	1	9	ok	9	ok
	2	10	weak	10	ok
	3	11	ok	11	ok
	4	12	ok	12	ok
	5	13	ok	13	ok
	6	14	ok	14	ok
	7	15	weak	15	ok
	8	16	ok	16	ok

Table 4: Tethered Sonobuoys During ACOMM LWAD 99-1

	R/V	Sonobuoy Depth	Sonobuoy RF Channel	TEAC Channel #
JD 037 21:50	SeaDiver	Shallow	8	31
JD 037 21:50	SeaDiver	Deep	10	32
JD 037 21:50	Edwin Link	Shallow	7	29
JD 037 21:50	Edwin Link	Deep	25	30
JD 038 05:57	Edwin Link	Shallow	13	31
JD 038 05:57	Edwin Link	Deep	9	32
JD 038 06:00	SeaDiver	Shallow	27	29
JD 038 06:20	SeaDiver	Deep	18	30
JD 038 14:06	SeaDiver	Shallow	2	29
JD 038 14:28	SeaDiver	Deep	13	30
JD 038 13:42	Edwin Link	Shallow	3	31
?	Edwin Link	Deep	?	?

Table 5: The Sparse DFE Equalizer Parameters

MFDTHRESH = 0.50 ;
intf = 2;
TH_SNR = 20.00 %TH_SNR =20.00
TH_SINR = 10.0 %TH_SINR = 20.0
TH_N_EST_RATIO = 0.30 ;
resamp_flim = 0.50 ;
FFC = 1.50 ;
PSC = 0.50 ;
FFLIM = 6 ;
dop_start =-10 ;
dop_end = 10 ;
dop_res = 0.1 ;
dlags = 5 ;
RESAMPTHRESH = 4.0e-04
RESAMP_LEN = 11.00 ;
resamp_filt_update =100;
resamp_filt_size = 11 ;
MSETHRESH = 10^(-20/10) ;
limitgain = 0.01 ;
pll = [0.0011 -0.001 0 ; 1 -2 1] ;
BUDGET = nsymbols;
lambda = 0.994 ;
%lambda = 0.995 ;
mu = 0.050 ;
dinit = 1000 ;
eqfcn = 'n2rlsv2'

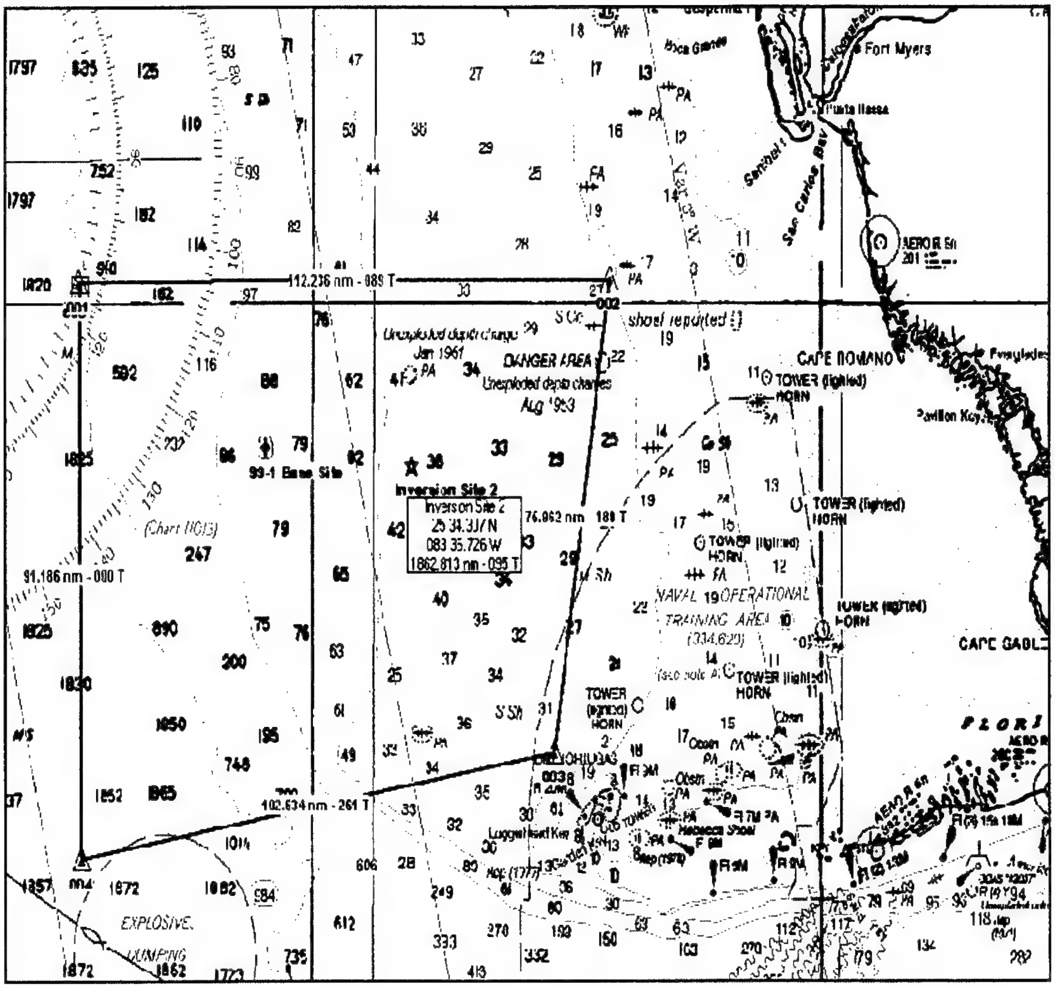

Figure 1: OPAREA of the LWAD99-1 experiment in the Gulf of Mexico.

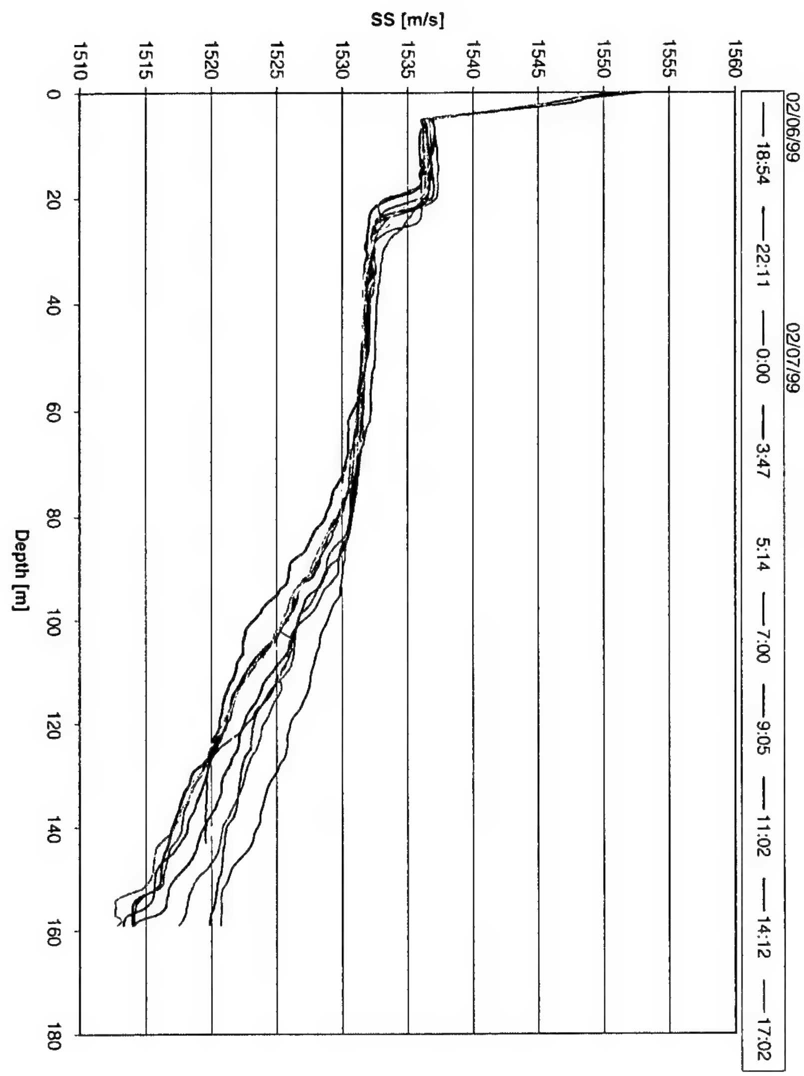

Figure 2: Sound speed profiles (SSP) during the LWAD99-1 ACOMM experiment.

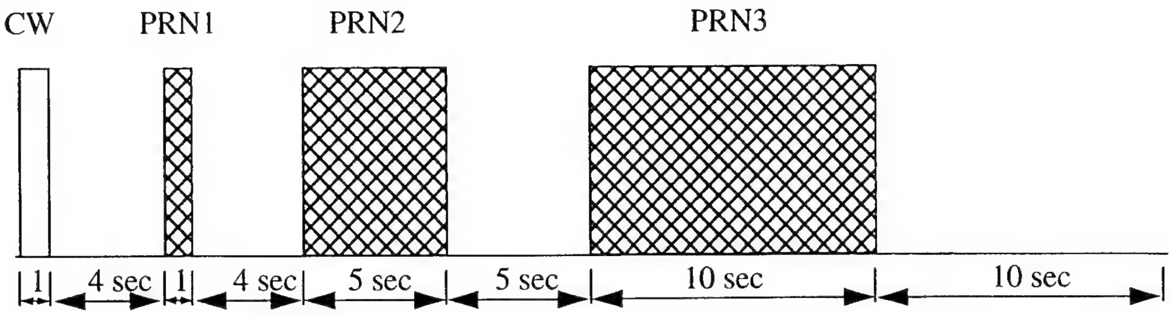

Figure 3: TX signal Pattern for the LWAD99-1 ACOMM experiment.

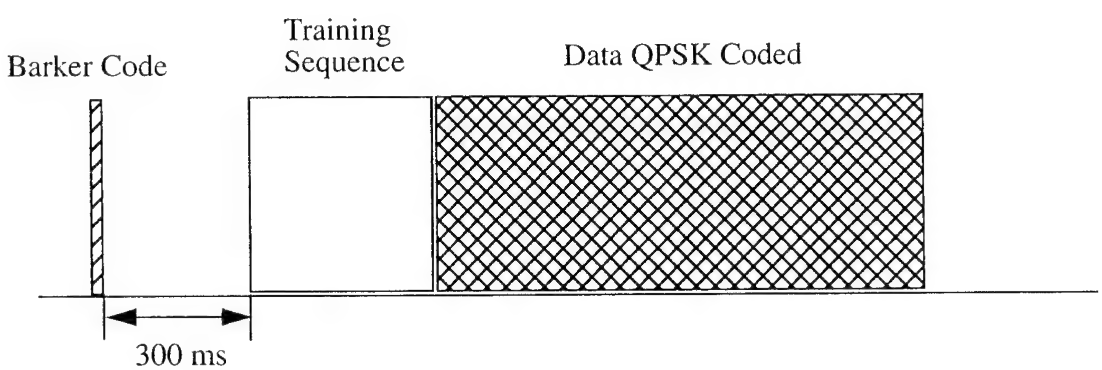

Figure 4: PRN signal structure for the ACOMM waveforms.

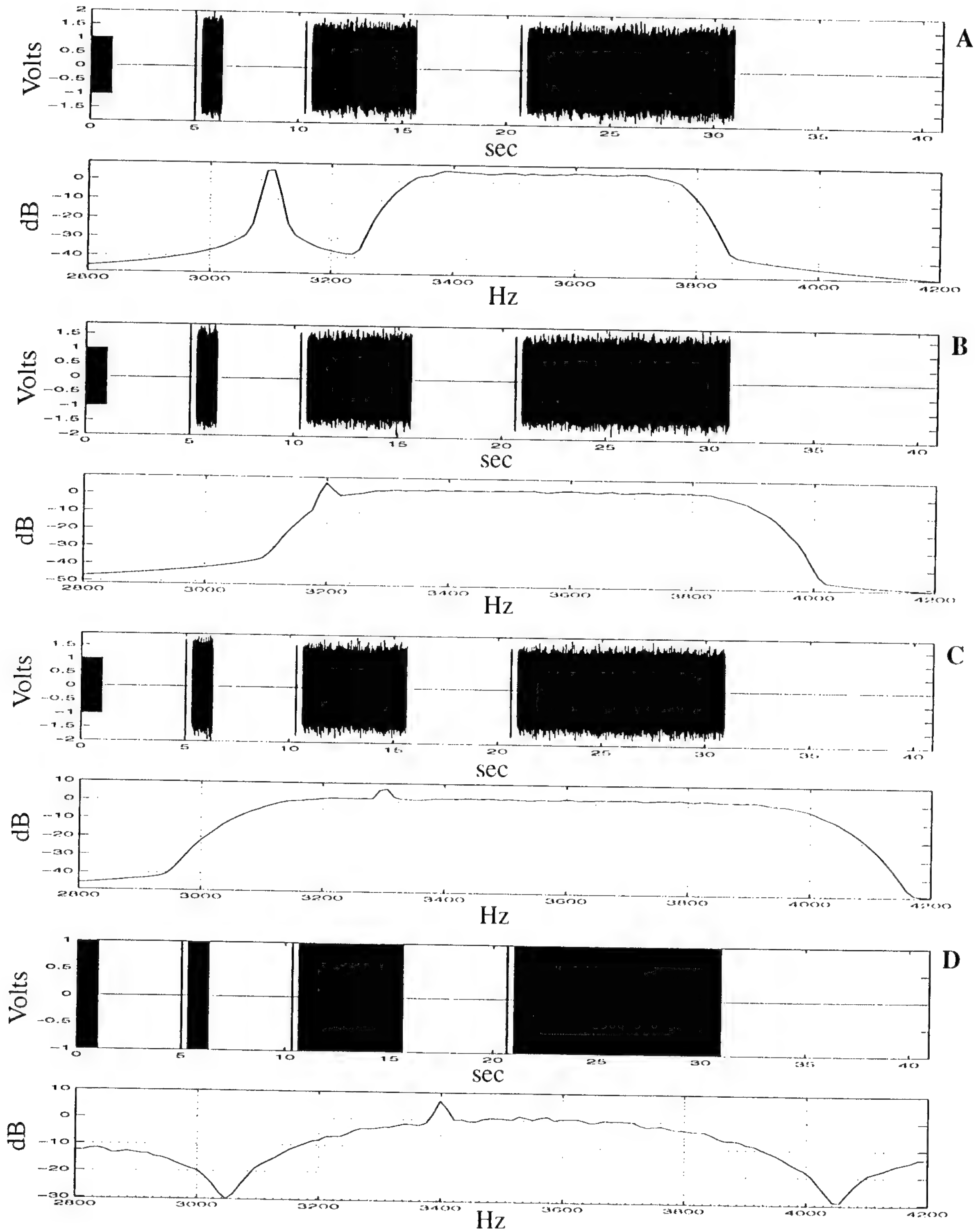

Figure 5: The ACOMM transmitted waveforms and their spectrums. A - CW at 3100 HZ and QPSK at 1000 b/s, B - CW at 3200 HZ and QPSK at 1500 b/s, C - CW at 3300 HZ and QPSK at 2000 b/s, D - CW at 3400 HZ and OQPSK at 1000 b/s.

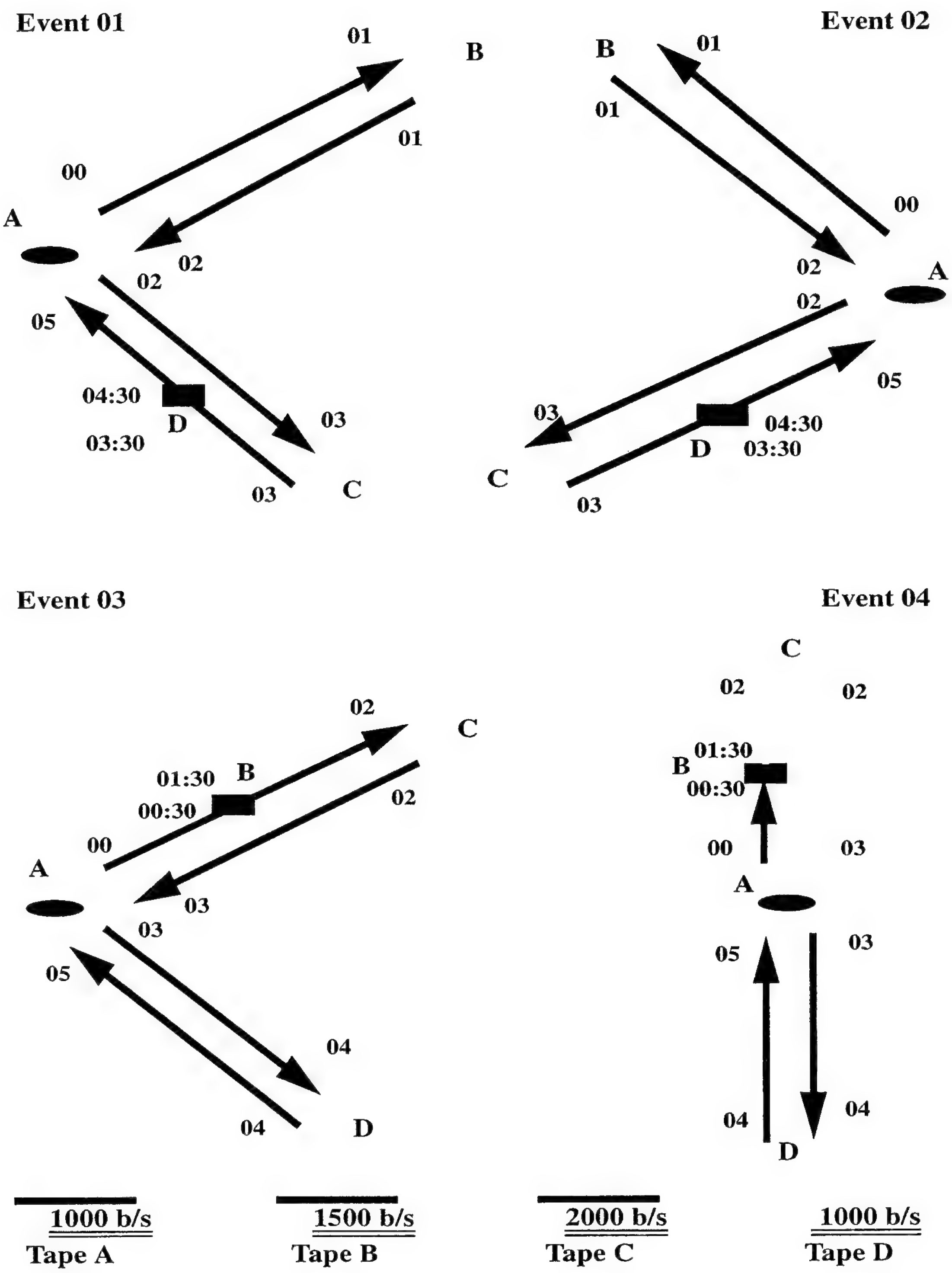

Figure 6: The planned (pre-experiment) tracks of the source ship (Gyre) and the planned waveform transmission along each track (Leg). The point A represents the mid point between the drifting platforms (SeaDiver and Edwin Link).

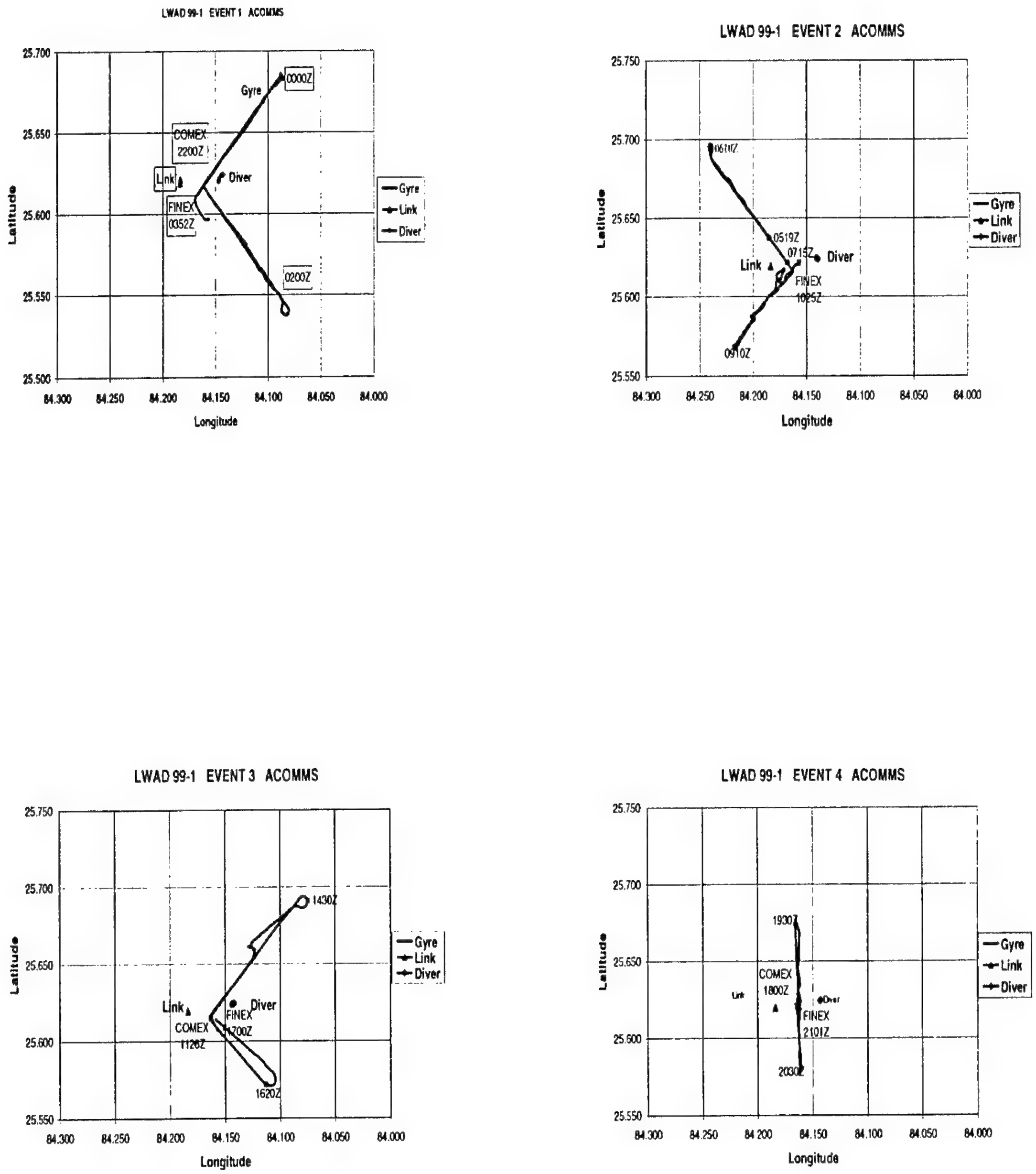

Figure 7: The R/V Gyre (source ship) track during the LWAD 99-1 ACOMM experiment. The R/V SeaDiver and the R/V Edwin Link (receiving ships) were drifting platforms..

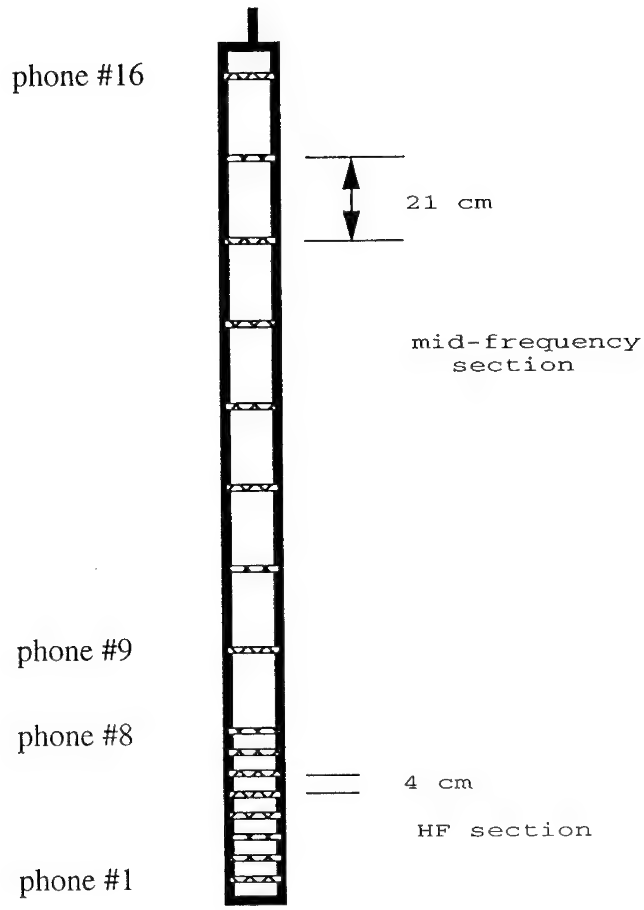

Figure 8: Descriptive schematics of the ACOMM VLA-A or VLA-B with 16 phones. The bottom 8 phones are spaced for 20 kHz, and the top 8 phones are spaced for 3.5 kHz.

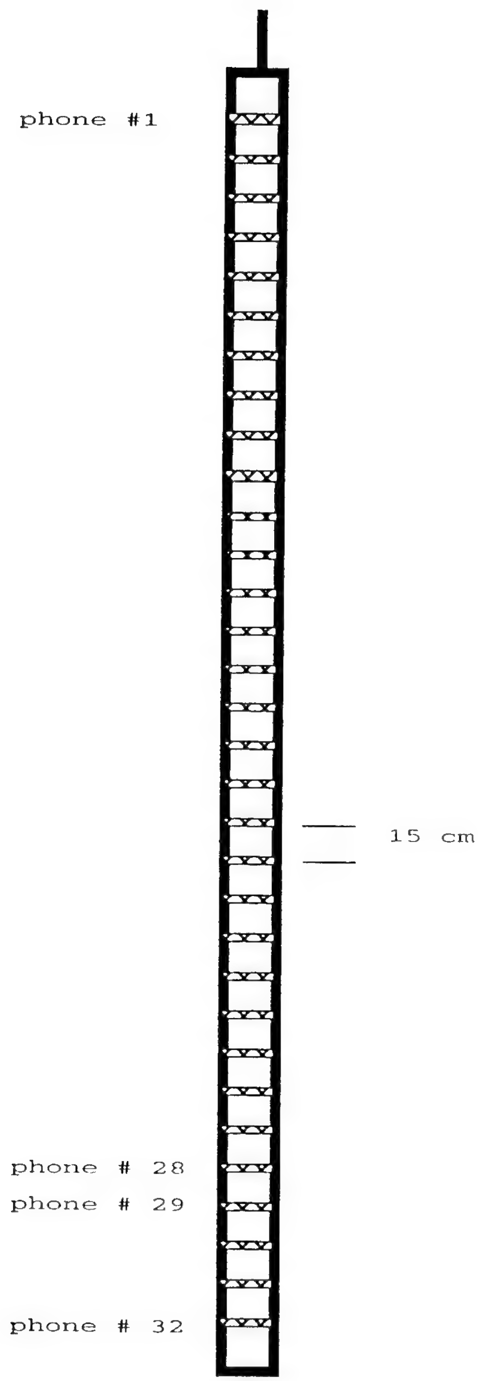

Figure 9: Descriptive schematics of the 32 element LWAD VLA.

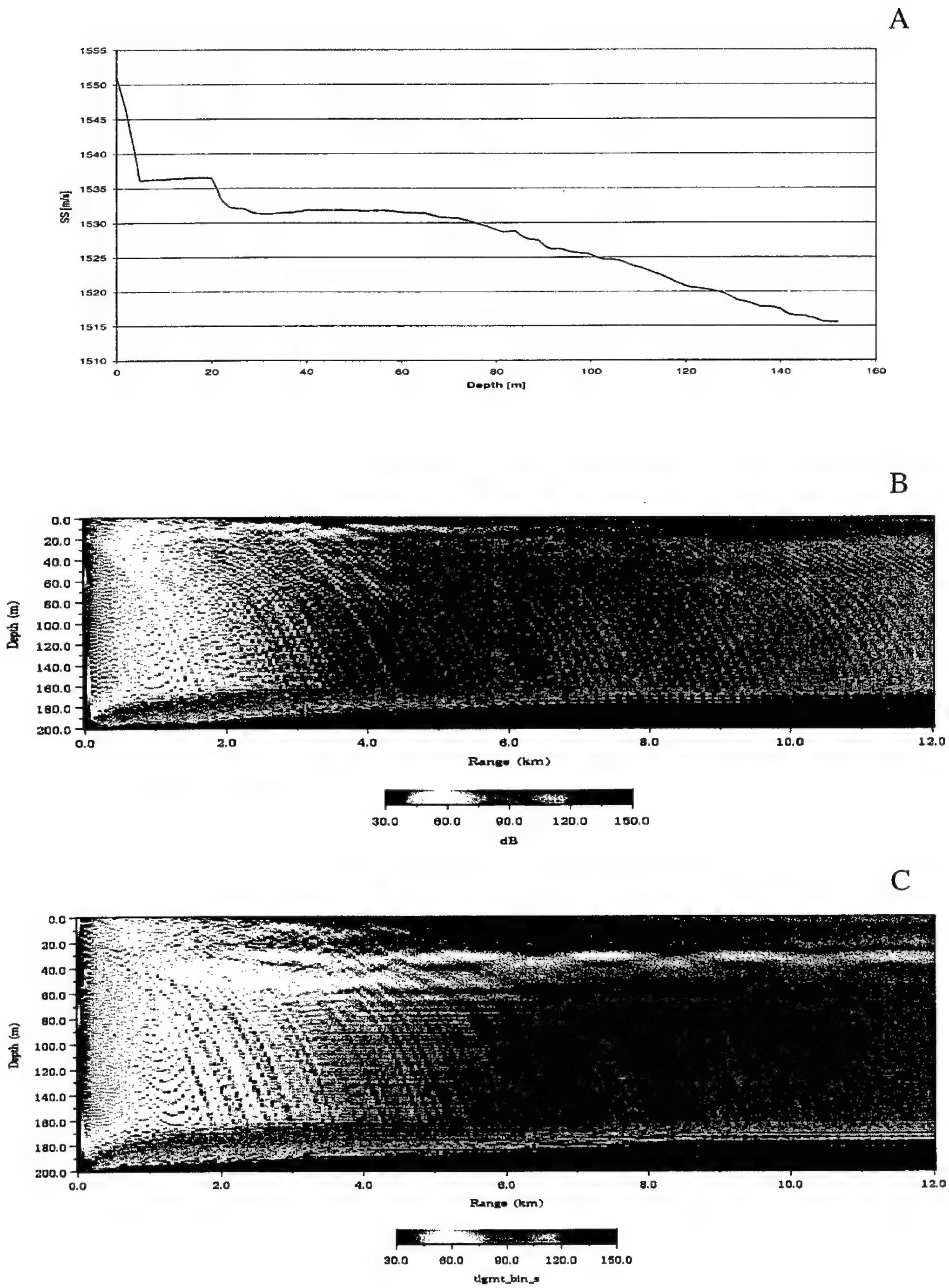

Figure 10: Transmission loss (TL) plots generated by a PE (parabolic equation) code and using a sample SSP (A) measured during the LWAD99-1 aboard the Edwin Link. (B) The TL where the source is at 20 m below the surface, and (C) the source is at 40 m bellow the surface.

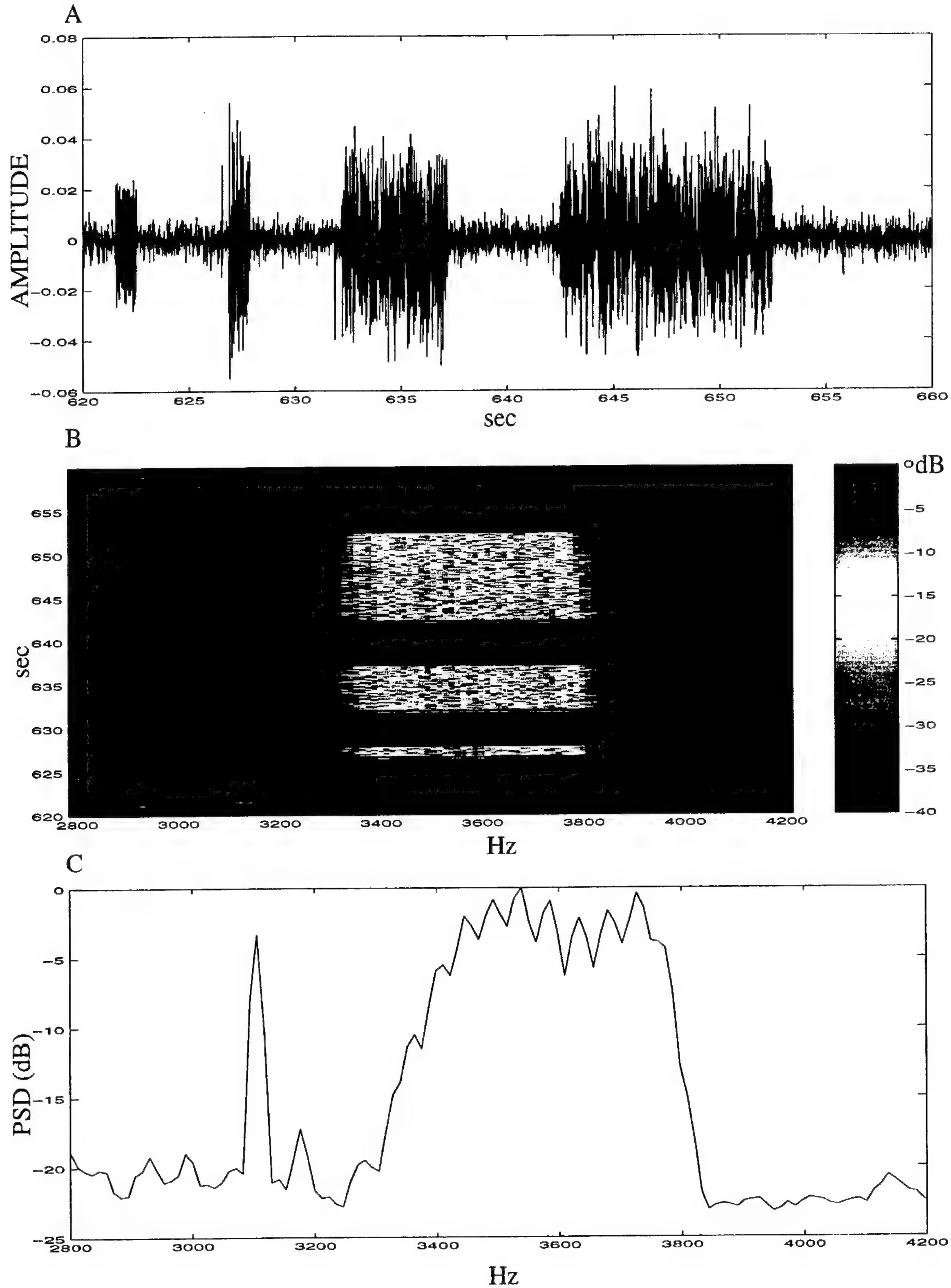

Figure 11: The received signal during event 04 Leg DA (A), its normalized spectrogram (B), and its power spectral density (PSD). In plots (A) and (B) 0 sec correspond to 20:45:30 zulu.

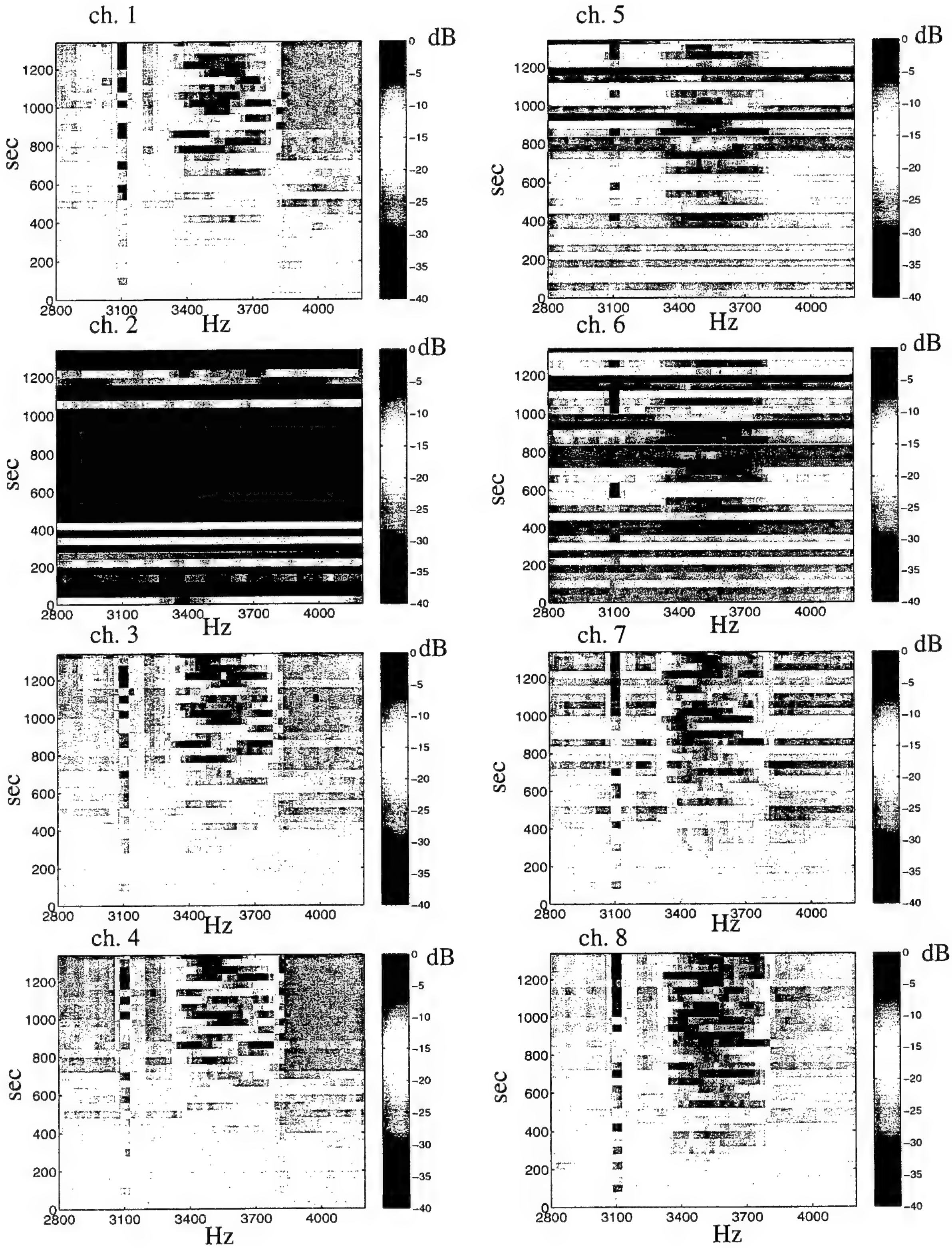

Figure 12: The spectrogram of the received signal during the ACOMM Event 04 Leg DA at the ACOMM VLA-B (phones 9 to 16 which correspond to channels 1 to 8 on the modem).

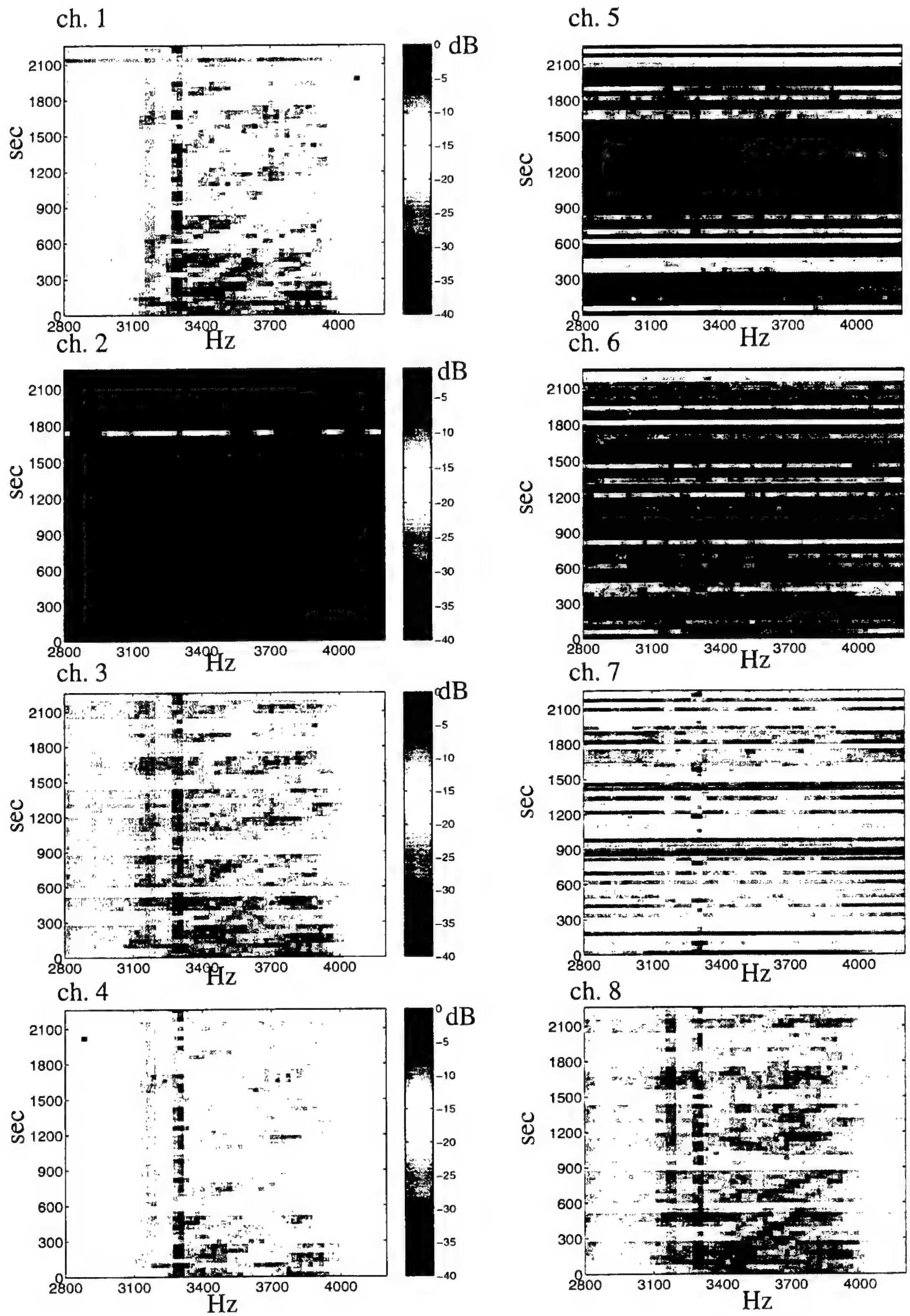

Figure 13: The spectrogram of the received signals during Event 04 Leg BB at VLA-B (phones 9 to 16). The CW at 3300 Hz and the QPSK at 2000 b/s.

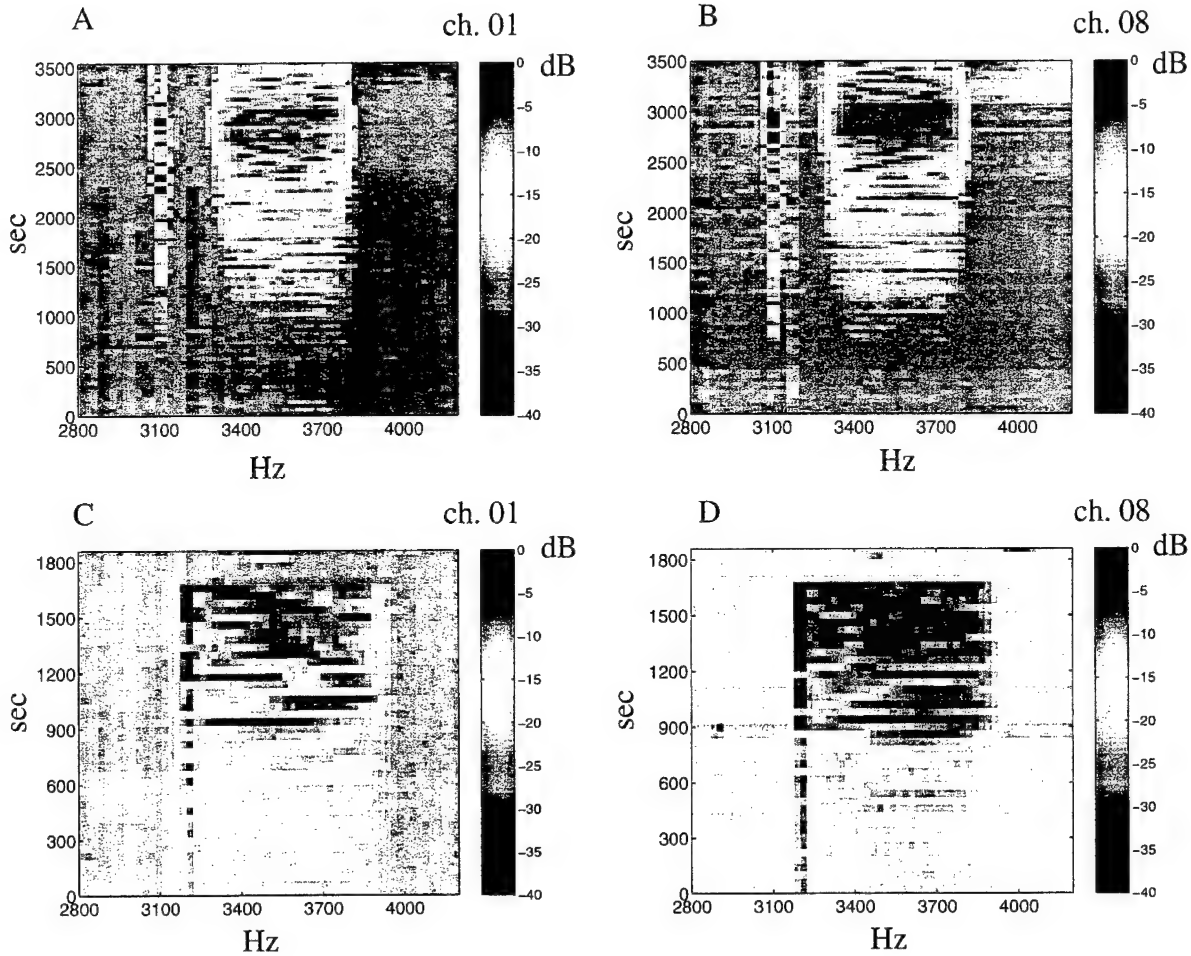

Figure 14: Received signal spectrogram during Event 03 on VLA-B. (A) and (B) received signal (PRN and CW) on phone 9 and 16 (ch. 1 and 8), respectively, along Leg CA. Plots (C) and (D) the same as (A) and (B) but along Leg DA.

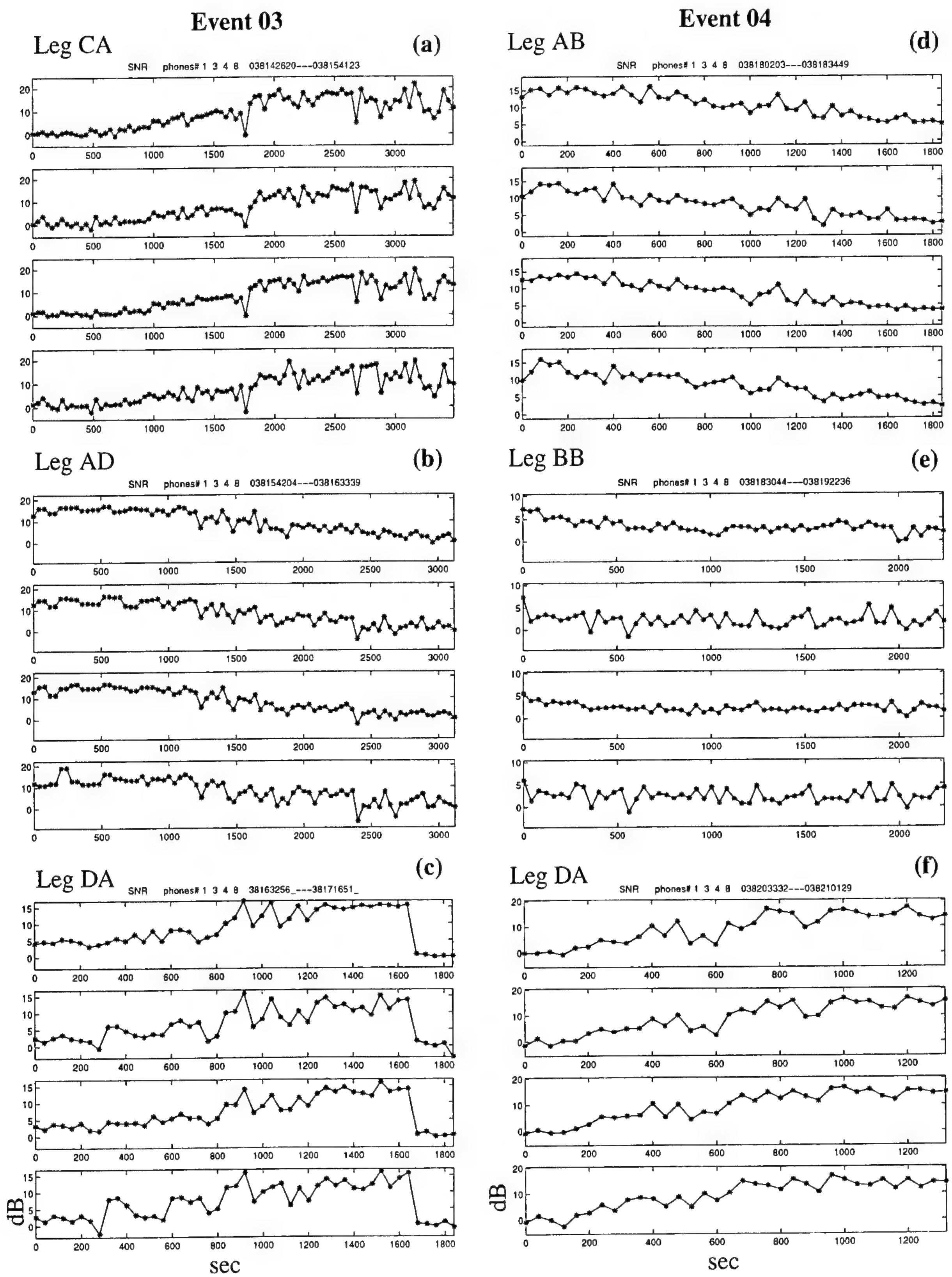

Figure 15: The SNR on channels 1, 3, 4, and 8 during event 03 along Legs CA, AD, and DA, and event 04 along Legs AB, BB, and DA.

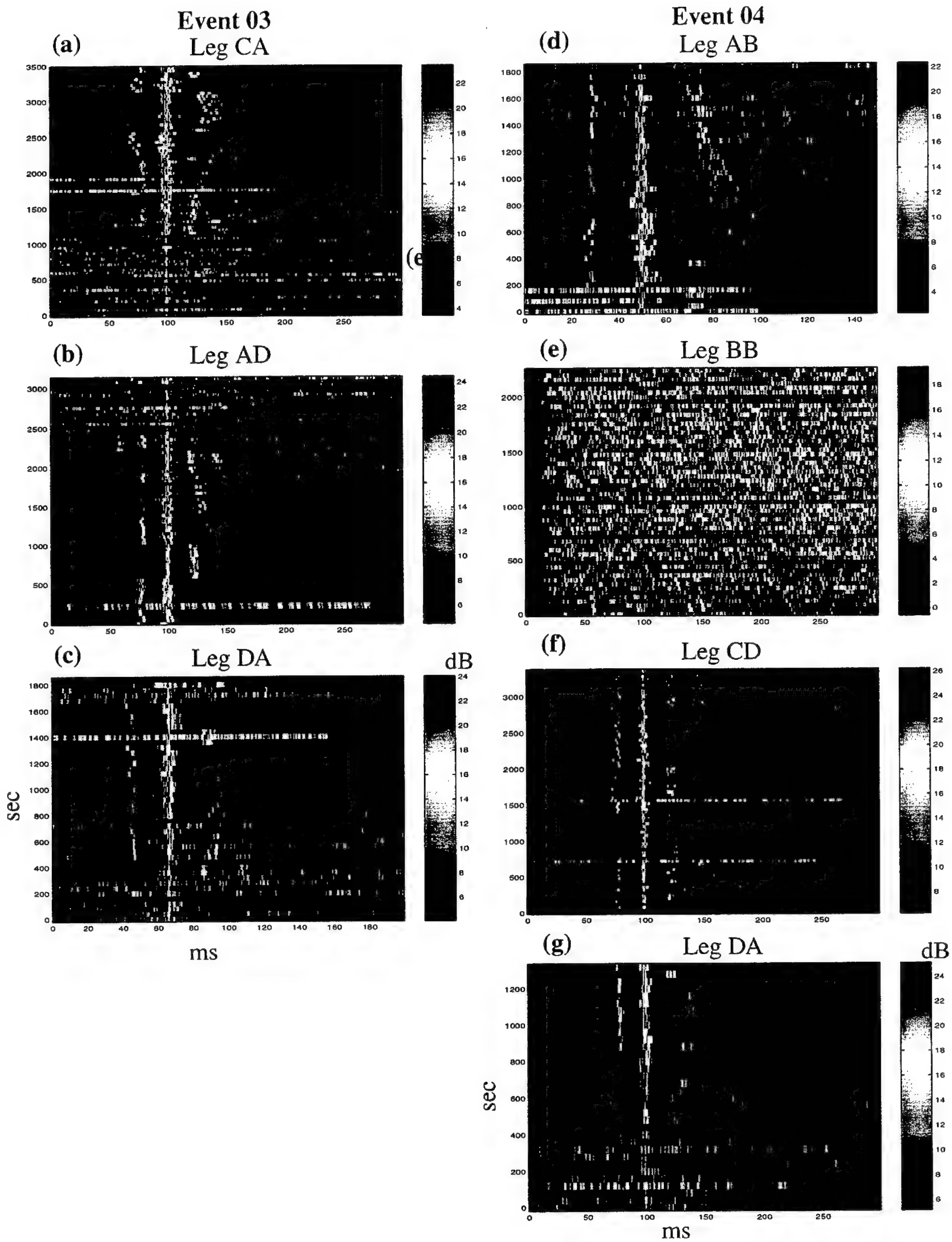

Figure 16: The channel impulse response estimation during event 03 along Legs CA,AD, DA; and event 04 along Legs AB, BB, CD, CA.

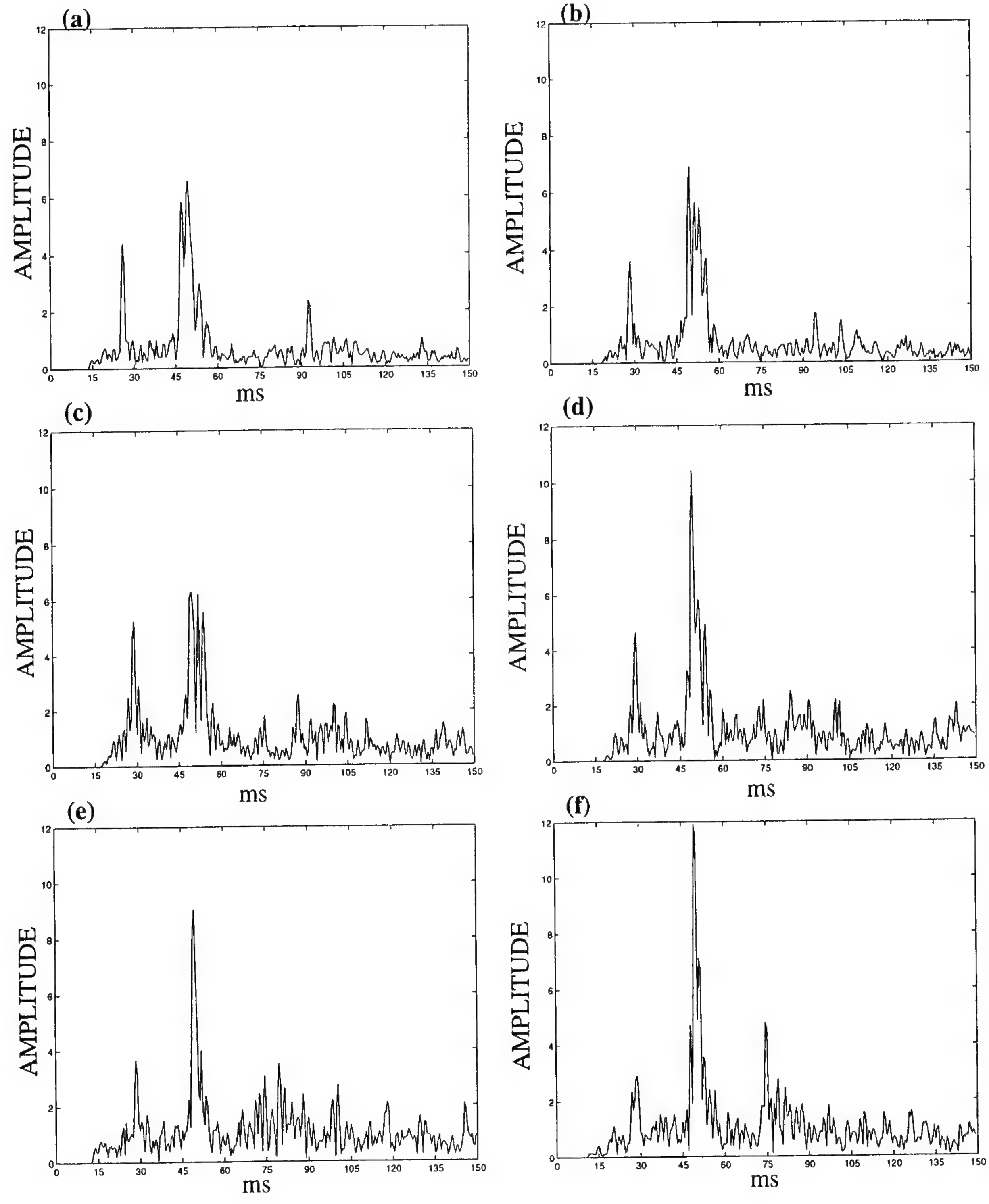

Figure 17: The channel impulse response during event 04 along Leg AB at 400 sec (a), 440 sec (b), 640 sec (c), 680 sec (d), 1200 sec (f), and 1240 sec (g) relative to the start of the run of event 04 Leg AB.

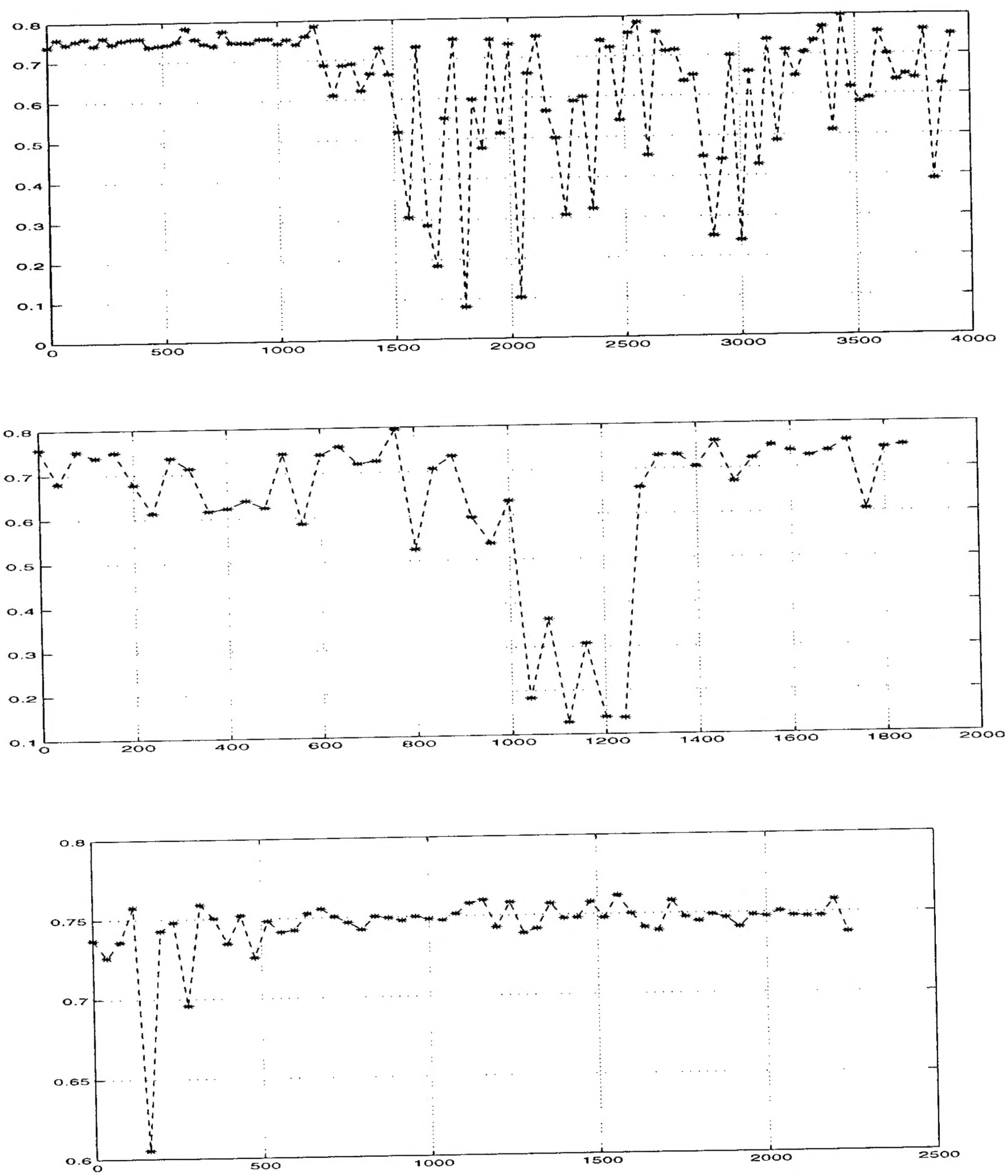

Figure 18: The BER of the equalized received signals on channel 1 during event 03 Leg CA (a); during event 04 Leg AB (b) , and event 04 Leg BB (c).

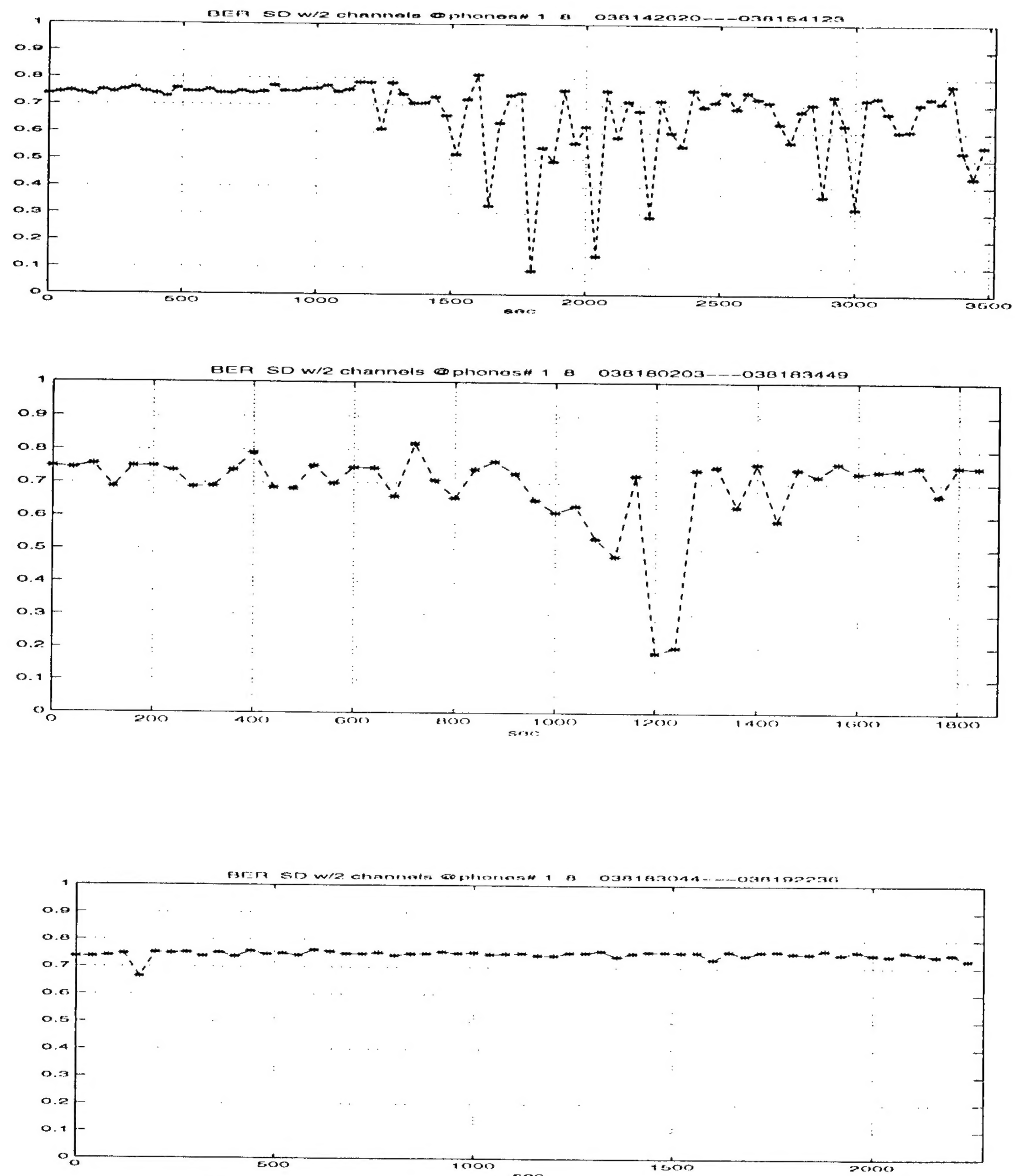

Figure 19: The BER of the equalized received signals (using spacial diversity) on channels 1 and 8 during event 03 Leg CA (a); during event 04 Leg AB (b) , and event 04 Leg BB (c).

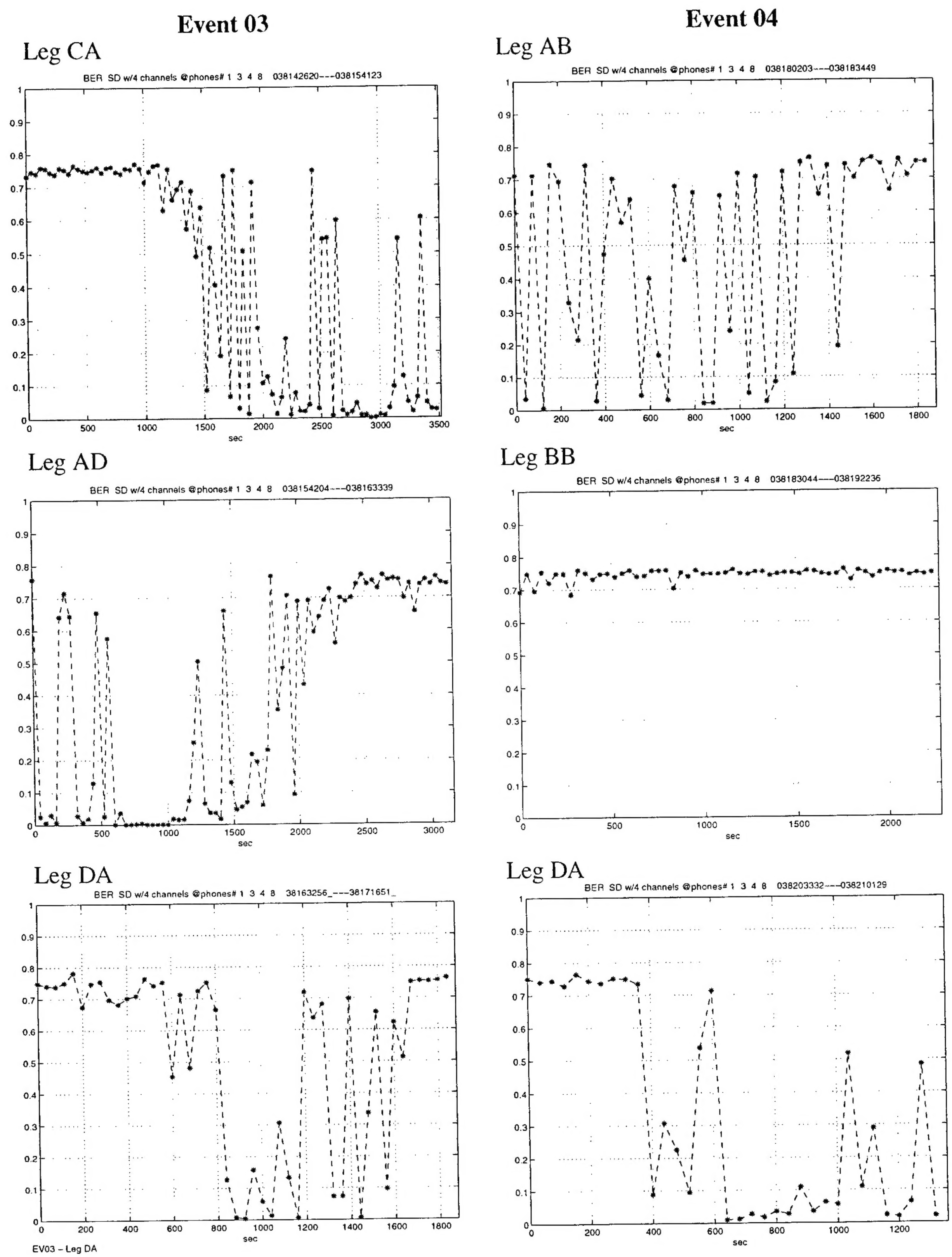

Figure 20: The BER of the equalized received signals (using spacial diversity) on channels 1, 3, 4, and 8 during event 03 and event 04.

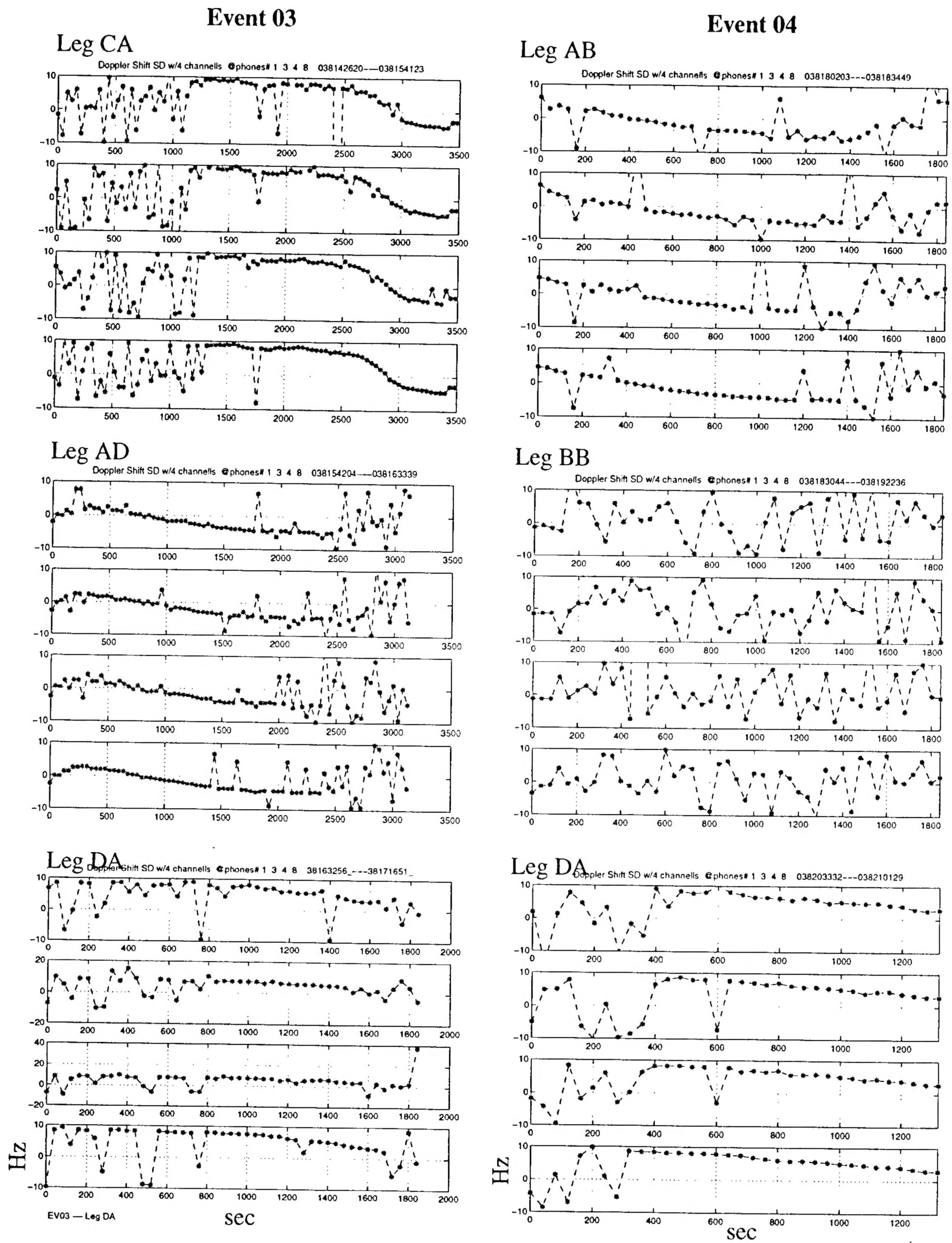

Figure 21: The Doppler shift estimate on channels 1, 3, 4, and 8 during event 03 along Legs CA, AD, and DA, and event 04 along Legs AB, BB, and DA.